U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-264 227

Design Criteria for Swine Waste Treatment Systems

North Carolina State Univ, Raleigh

Prepared for

Robert S Kerr Environmental Research Lab, Ada, Okla

Oct 76

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-76-233	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE DESIGN CRITERIA FOR SWINE WASTE TREATMENT SYSTEMS		5. REPORT DATE October 1976 (Issuing Date) 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Frank J. Humenik and Michael R. Overcash		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Biological and Agricultural Engineering Department North Carolina State University Raleigh, North Carolina 27607		10. PROGRAM ELEMENT NO. 1HB617 11. CONTRACT/GRANT NO. R-802203
12. SPONSORING AGENCY NAME AND ADDRESS Robert S. Kerr Environmental Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Ada, Oklahoma 74820		13. TYPE OF REPORT AND PERIOD COVERED Final Report (6/71-5/74) 14. SPONSORING AGENCY CODE EPA/600/15

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Coordinated laboratory, field pilot-, and farm-scale lagoon studies were conducted to define relationships between loading intensity and frequency based on treatment performance, sludge accumulation, and odor potential. Surface aeration of field pilot units and farm-scale lagoons was also investigated to evaluate aeration levels required for odor control and the effect of surface aeration on nitrogen and organic transformations.

Laboratory studies were designed to elucidate basic chemical, physical, and biological mechanisms important in explaining and modeling lagoon performance. Long-term mass balance studies were conducted to define the fate of waste input and thus total constituent loss from the system.

Predictive and interpretive relationships for lagoons based on constant batch loading and continuous loading were derived to describe the supernatant concentration of unaerated lagoons. Methods for determining steady-state concentrations and first-order reaction rate constants for oxygen demand, organic carbon, and nitrogen were developed and compared with laboratory and field pilot-scale data.

Lagoon liquid from a farm-scale unit was irrigated to nine 9.24 m x 9.24 m Coastal Plain soil-Bermuda grass plots at nitrogen loading rates of 300, 600, and 1,200 kg N/ha./year. Mass balance data were collected to determine the fate of applied waste constituents.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Swine; Agricultural Wastes	Treatment Processes; Aerated Lagoons	02/A, C, E

18. DISTRIBUTION STATEMENT RELEASE UNLIMITED	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 316
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

*USGPO: 1977 — 757-056/5460 Region 5-II

PB 264 227

EPA-600/2-76-233
October 1976

Environmental Protection Technology Series

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into five series. These five broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The five series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies

This report has been assigned to the ENVIRONMENTAL PROTECTION TECHNOLOGY series. This series describes research performed to develop and demonstrate instrumentation, equipment, and methodology to repair or prevent environmental degradation from point and non-point sources of pollution. This work provides the new or improved technology required for the control and treatment of pollution sources to meet environmental quality standards.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

EPA-600/2-76-233
October 1976

DESIGN CRITERIA FOR SWINE WASTE TREATMENT SYSTEMS

By

Frank J. Humenik
Michael R. Overcash
Biological and Agricultural Engineering Department
North Carolina State University
Raleigh, North Carolina 27607

Grant No. R-802203

Project Officer

Lynn R. Shuyler
Agricultural Wastes Section
Robert S. Kerr Environmental Research Laboratory
Ada, Oklahoma 74820

ROBERT S. KERR ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
ADA, OKLAHOMA 74820

DISCLAIMER

This report has been reviewed by the Robert S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

ABSTRACT

Coordinated laboratory, field pilot-, and farm-scale lagoon studies were conducted to define relationships between loading intensity and frequency based on treatment performance, sludge accumulation, and odor potential. Surface aeration of field pilot units and farm-scale lagoons was also investigated to evaluate aeration levels required for odor control and the effect of surface aeration on nitrogen and organic transformations.

Laboratory studies were designed to elucidate basic chemical, physical, and biological mechanisms important in explaining and modeling lagoon performance. Long-term mass balance studies were conducted to define the fate of waste input and thus total constituent loss from the system.

Predictive and interpretive relationships for lagoons based on constant batch loading and continuous loading were derived to describe the supernatant concentration of unaerated lagoons. Methods for determining steady-state concentrations and first-order reaction rate constants for oxygen demand, organic carbon, and nitrogen were developed and compared with laboratory and field pilot-scale data.

Lagoon liquid from a farm-scale unit was irrigated to nine 9.24 m x 9.24 m Coastal Plain soil-Bermuda grass plots at nitrogen loading rates of 300, 600, and 1,200 kg N/ha./year. Mass balance data were collected to determine the fate of applied waste constituents.

Analytical technique evaluations lead to recommendation of the 15-minute digestion period for the standard chemical oxygen demand (COD) test. The suitability of simplified portable laboratory methods for nitrogen and phosphorus and selective electrode procedures for nitrate and ammonia nitrogen were evaluated by comparison with results according to standard wet chemistry procedures.

This report was submitted in fulfillment of Contract Number R-802203, Program Element 1D2072, by North Carolina State University, Biological and Agricultural Engineering, under the partial sponsorship of the Environmental Protection Agency. Work was completed as of December 1, 1975.

CONTENTS

Sections		Page
I	Conclusions	1
II	Recommendations	10
III	Introduction	13
	General	13
	Project Objectives	14
	Scope and Purpose	15
IV	Literature Review	18
	Swine Production Trends	18
	Properties of Swine Waste	18
	Overview of Lagoons	20
	Overview of Land Application	29
V	Lagoon Studies	33
	Sampling and Analytical Procedures	33
	Definition of Reference Loading Rate	40
	Swine Waste Characterization for Experimental Studies	40
	Laboratory Scale Experiments	46
	Field Pilot-Scale Experiments	105
	Farm-Scale Lagoon	153
VI	Predictive and Interpretive Relationships for Lagoons	163
	Batch Loading Approach	164
	Continuous Loaded Approach - Organics	171
	Continuous Loaded Approach - Nitrogen	184
VII	Land Application Studies	190
	Experimental Procedures	190
	Field Results and Discussion	197

Preceding page blank

CONTENTS (Continued)

Sections		Page
VIII	References	244
IX	List of Resultant Publications	252
X	Appendices	256
	Laboratory Data	257
	Lagoon Data	279
	Land Application Data	287

LIST OF FIGURES

Number		Page
1	Schematic of shear-type blender head located inside blending container utilized for raw waste sample preparation, stainless steel construction	35
2	Comparison of ammonia analysis by ion specific electrode and standard distillation techniques for swine and poultry waste	38
3	Schematic of sludge management experiment with one-liter Imhoff cones loaded with swine waste	47
4	Supernatant COD concentration changes in Imhoff cones begun with swine waste lagoon supernatant with or without sludge as inoculum and loaded with raw swine waste (first experimental set - once/week)	49
5	Supernatant TOC concentration changes in Imhoff cones begun with swine waste lagoon supernatant with or without sludge as inoculum and loaded with raw swine waste (first experimental set - once/week)	50
6	Supernatant TKN concentration changes in Imhoff cones begun with swine waste lagoon supernatant with or without sludge as inoculum and loaded with raw swine waste (first experimental set - once/week)	51
7	Supernatant o-PO_4-P concentration changes in Imhoff cones begun with swine waste lagoon supernatant with or without sludge as inoculum and loaded with raw swine waste (first experimental set - once/week)	52
8	Supernatant COD concentration changes in Imhoff cones begun with swine waste lagoon supernatant with or without sludge as inoculum and loaded with raw swine waste (first experimental set - thrice/week)	53
9	Supernatant TOC concentration changes in Imhoff cones begun with swine waste lagoon supernatant with or without sludge as inoculum and loaded with raw swine waste (first experimental set - thrice/week)	54

LIST OF FIGURES (Continued)

10 Supernatant TKN concentration changes in Imhoff cones begun with swine waste lagoon supernatant with or without sludge as inoculum and loaded with raw swine waste (first experimental set - thrice/week) 55

11 Supernatant o-PO_4-P concentration changes in Imhoff cones begun with swine waste lagoon supernatant with or without sludge as inoculum and loaded with raw swine waste (first experimental set - thrice/week) 56

12 Supernatant COD concentration changes in Imhoff cones begun with tap water and loaded with raw swine waste (second experimental set - reference rate) 60

13 Supernatant TOC concentration changes in Imhoff cones begun with tap water and loaded with raw swine waste (second experimental set - reference rate) 61

14 Supernatant TKN concentration changes in Imhoff cones begun with tap water and loaded with raw swine waste (second experimental set - reference rate) 62

15 Supernatant COD concentration changes in Imhoff cones begun with tap water and loaded with raw swine waste (second experimental set - four times reference) 63

16 Supernatant TOC concentration changes in Imhoff cones begun with tap water and loaded with raw swine waste (second experimental set - four times reference) 64

17 Supernatant TKN concentration changes in Imhoff cones begun with tap water and loaded with raw swine waste (second experimental set - four times reference) 65

18 Supernatant TKN and NH_3-N changes associated with removal of the evaporative loss reduction cover from the Imhoff cones 71

19 Microbial population and supernatant COD concentration changes immediately after loading laboratory reactors 73

20 Schematic of 14-l laboratory reactor loaded with swine wastes 77

LIST OF FIGURES (Continued)

21 Supernatant COD concentration changes in 14-1 laboratory reactors loaded with swine waste at various frequencies 78

22 Supernatant TOC concentration changes in 14-1 laboratory reactors loaded with swine waste at various frequencies 79

23 Supernatant TKN concentration changes in 14-1 laboratory reactors loaded with swine waste at various frequencies 80

24 Supernatant o-PO_4-P concentration changes in 14-1 laboratory reactors loaded with swine waste at various frequencies 81

25 Supernatant COD concentration changes in laboratory 14-1 reactors with the nominal reference loading rate of swine waste on a continuous or batch basis 86

26 Supernatant TOC concentration changes in laboratory 14-1 reactors with the nominal reference loading rate of swine waste on a continuous or batch basis 87

27 Supernatant TKN and o-PO_4-P concentration changes in laboratory 14-1 reactors with the nominal reference loading rate of swine waste on a continuous or batch basis 88

28 Supernatant COD and TOC concentration changes in laboratory 14-1 reactors with four times the nominal reference loading rate of swine waste on a continuous or batch basis 89

29 Supernatant TKN concentration changes in laboratory 14-1 reactors with four times the nominal reference loading rate of swine waste on a continuous or batch basis 90

30 Supernatant o-PO_4-P concentration changes in laboratory 14-1 reactors with four times the nominal reference loading rate of swine waste on a continuous or batch basis 91

LIST OF FIGURES (Continued)

31 Supernatant COD and TOC concentration changes in laboratory 14-l reactors with 0.6 times the reference loading rate of swine waste and once per week frequency 93

32 Supernatant TKN concentration changes in laboratory 14-l reactors with 0.6 times the reference loading rate of swine waste and once per week frequency 94

33 Supernatant o-PO_4-P concentration changes in laboratory 14-l reactors with 0.6 times the reference loading rate of swine waste and once per week frequency 95

34 Supernatant COD and TOC concentration changes in laboratory 14-l reactors with 0.3 times the reference loading rate of swine waste and once per week frequency 96

35 Supernatant TKN concentration changes in laboratory 14-l reactors with 0.3 times the reference loading rate of swine waste and once per week frequency 97

36 Supernatant o-PO_4-P concentration changes in laboratory 14-l reactors with 0.3 times the reference loading rate of swine waste and once per week frequency 98

37 Supernatant TOC concentration changes in laboratory 14-l reactors with 10.8 times the reference rate of swine waste 100

38 Supernatant TKN and o-PO_4-P concentration changes in laboratory 14-l reactors with 10.8 times the reference rate of swine waste 101

39 Schematic of pilot-scale lagoon research site 106

40 Photograph of pilot-scale lagoon research site 107

41 Supernatant COD and TOC concentration changes (two-week averages) in field pilot-scale lagoons loaded once per week at four times the reference rate for swine wastes 110

LIST OF FIGURES (Continued)

42 Supernatant TKN and o-PO_4-P concentration (two-week averages) in field pilot-scale lagoons loaded once per week at four times the reference rate for swine wastes 111

43 Supernatant COD and TOC concentration changes (two-week averages) in field pilot-scale lagoons loaded once per week at the reference rate for swine wastes 112

44 Supernatant TKN and o-PO_4-P concentration changes (two-week averages) in field pilot-scale lagoons loaded once per week at the reference rate for swine wastes 113

45 Supernatant COD and TOC concentration changes (two-week averages) in field pilot-scale lagoon receiving effluent from lagoon loaded once per week at reference rate for swine wastes 114

46 Supernatant TKN concentration changes (two-week averages) in field pilot-scale lagoon receiving effluent from lagoon loaded once per week at reference rate for swine wastes 115

47 Supernatant COD and TOC concentration changes (two-week averages) in third lagoon of three-unit series with the first lagoon of this field pilot-scale series loaded once per week at the reference rate for swine waste 116

48 Supernatant TKN concentration changes (two-week averages) in third lagoon of three-unit series with the first lagoon of this field pilot-scale series loaded once per week at the reference rate for swine waste 117

49 Supernatant TKN and o-PO_4-P concentration changes (two-week averages) in field pilot-scale lagoons loaded once per week at 0.5 times the reference rate for swine waste 118

50 Supernatant TKN and o-PO_4-P concentration changes (two-week averages) in field pilot-scale lagoons loaded once per week at 0.5 times the reference rate for swine waste 119

LIST OF FIGURES (Continued)

51 Supernatant COD and TOC concentration changes (two-week averages) in field pilot-scale lagoons loaded once per week at 0.25 times the reference rate for swine wastes 120

52 Supernatant TKN and o-PO_4-P concentration changes (two-week averages) in field pilot-scale lagoons loaded once per week at 0.25 times the reference rate for swine wastes 121

53 Supernatant COD and TOC concentration changes (two-week averages) in field pilot-scale lagoons loaded once per week at 0.125 times the reference rate for swine wastes 122

54 Supernatant TKN and o-PO_4-P concentration changes (two-week averages) in field pilot-scale lagoons loaded once per week at 0.125 times the reference rate for swine wastes 123

55 Supernatant COD and TOC concentration changes (two-week averages) in field pilot-scale lagoons loaded once per week at 0.0625 times the reference rate for swine wastes 124

56 Supernatant TKN and o-PO_4-P concentration changes (two-week averages) in field pilot-scale lagoons loaded once per week at 0.0625 times the reference rate for swine wastes 125

57 Supernatant COD and TOC concentration changes (two-week averages) in field pilot-scale lagoons loaded once per week at 0.031 times the reference rate for swine wastes 126

58 Supernatant TKN and o-PO_4-P concentration changes (two-week averages) in field pilot-scale lagoons loaded once per week at 0.031 times the reference rate for swine wastes 127

59 Liquid TOC and TKN concentration as a function of depth in an unaerated, anaerobic, pilot-scale field lagoon loaded at the reference rate with swine waste 130

LIST OF FIGURES (Continued)

60 Schematic of aerated pilot-scale lagoon with water level control for fixed surface aerator 143

61 Supernatant COD concentration for field pilot-scale lagoons with surface aeration loaded once per week at 2 times the reference rate for swine wastes 144

62 Supernatant TOC concentration for field pilot-scale lagoons with surface aeration loaded once per week at 2 times the reference rate for swine wastes 145

63 Supernatant TKN concentration for field pilot-scale lagoons with surface aeration loaded once per week at 2 times the reference rate for swine wastes 146

64 Supernatant $o\text{-}PO_4\text{-}P$ concentration for field pilot-scale lagoons with surface aeration loaded once per week at 2 times the reference rate for swine wastes 147

65 Depth profile of orthophosphorus concentration for pilot-scale swine lagoons receiving different rates of surface aeration 150

66 Supernatant TKN concentration and contributory liveweight changes for an on-farm swine waste lagoon loaded at once per day or more frequency (Clayton) 156

67 Supernatant COD concentration changes for an on-farm lagoon for swine wastes loaded at once per day or more frequency as waste material runs into lagoon 157

68 Supernatant TOC concentration changes for an on-farm lagoon for swine wastes loaded at once per day or more frequency as waste material runs into lagoon 158

69 Schematic of actual lagoon supernatant concentration with batch loading operation 165

70 Steady-state supernatant COD and TOC concentrations for laboratory reactors (14 liters) loaded once per week with swine waste (44,000 mg COD/1, 15,000 mg TOC/1) 170

LIST OF FIGURES (Continued)

71 Parametric plot of Equation (20) showing linear dependence of steady-state concentration on loading rate at high reaction rate constants 177

72 Steady-state supernatant COD concentrations for pilot-scale swine lagoons receiving various loading rates - experimental and predicted results (Equation 21) 182

73 Steady-state supernatant TOC concentration for pilot-scale swine lagoons receiving various loading rates - experimental and predicted results (Equation 21) 183

74 Steady-state supernatant TKN concentration for pilot-scale swine lagoons receiving various loading rates - experimental and predicted results (Equation 26) 188

75 Schematic diagram of facility developed to evaluate lagoon pretreatment - land application system for swine waste (Clayton) 191

76 Schematic of experimental plots for land application of swine lagoon effluent 193

77 Schematic of soil and water sampling profile in experimental plots for land application of swine lagoon effluent 195

78 Soil profile total Kjeldahl nitrogen concentrations for first-year application of swine lagoon effluent, 1973, at 1,200 and 300 kg N/ha. 224

79 Soil profile nitrate concentrations for first-year application of swine lagoon effluent, 1973, at 1,200 and 300 kg N/ha. 225

80 Soil profile calcium concentrations for first-year application of swine lagoon effluent, 1973, at 1,200 and 300 kg N/ha. 227

81 Soil profile magnesium concentrations for first-year application of swine lagoon effluent, 1973, at 1,200 and 300 kg N/ha. 228

LIST OF FIGURES (Continued)

82 Soil profile phosphorous concentrations for first-year application of swine lagoon effluent, 1973, at 1,200 and 300 kg N/ha. 229

83 Soil profile potassium concentrations for first-year application of swine lagoon effluent, 1973, at 1,200 and 300 kg N/ha. 230

84 Soil profile sodium concentrations for first-year application of swine lagoon effluent, 1973, at 1,200 and 300 kg N/ha. 231

85 Soil profile chloride concentrations for first-year application of swine lagoon effluent, 1973, at 1,200 and 300 kg N/ha. 232

86 Soil profile manganese concentrations for first-year application of swine lagoon effluent, 1973, at 1,200 and 300 kg N/ha. 234

87 Soil profile iron concentrations for first-year application of swine lagoon effluent, 1973, at 1,200 and 300 kg N/ha. 235

88 Soil profile copper concentrations for first-year application of swine lagoon effluent, 1973, at 1,200 and 300 kg N/ha. 236

89 Soil profile zinc concentrations for first-year application of swine lagoon effluent, 1973, at 1,200 and 300 kg N/ha. 237

LIST OF TABLES

Number		Page
1	Anaerobic Lagoon Loading Rates	24
2	Representative Summary of Various Parameter Concentrations for Blended and Unblended Samples	34
3	Variability of COD Analyses for Raw Waste Samples Using Shear Blender, Sample Weighing and Dilution for This Experimental Study	36
4	Reference Loading Rate Utilized in Anaerobic Lagoon Experiments Expressed in Units Commonly Reported	41
5	Mean Concentrations of Raw Swine Waste as Used For Input to Laboratory and Field Pilot Scale Experiments	43
6	Waste Generation from Under Slat Pit Receiving Swine Waste	44
7	Chemical Parameter Ratios of Various Sources of Swine Waste	45
8	Sludge or Settled Solids Recovery for Several Sludge Management Techniques from Imhoff Cones Receiving Swine Waste Inputs - First Experiment	57
9	Sludge or Settled Solids Recovery for Several Sludge Management Techniques from Imhoff Cones Receiving Swine Waste Inputs - Second Experiment	59
10	Initial Settling of Swine Wastes Evaluated from Imhoff Cone Anaerobic Reactors (No Sludge)	67
11	Relative Supernatant and Sludge Removal Levels for Imhoff Cones with Accumulated Sludge and Loaded with Swine Waste	69
12	Samples Taken at Several Depths in Imhoff Cone and 16-1 Laboratory Reactors Loaded with Swine Wastes	74

LIST OF TABLES (Continued)

13 Overall Mass Balance Results for Anaerobic Treatment of Swine Wastes - Imhoff Cone Reactors with Various Sludge Managements 75

14 Amount of Waste Parameters Remaining in Sludge Zone of Anaerobic 14-Liter Laboratory Reactors Loaded at Different Frequencies 82

15 Comparison of the Amounts of Various Pollutional Parameters in the Sludge Zone (Bottom 2.8 cm) and the Sludge Plus Lower Supernatant Zone (Bottom 6.4 cm) 83

16 Sludge Accumulation for Swine Waste Input to Anaerobic Laboratory Reactors 84

17 Overall Mass Balance for 14-1 Anaerobic Laboratory Reactors Loaded with Raw Swine Waste at Various Frequencies 85

18 Removal Efficiencies (Equation 2) of Various Pollutional Parameters from 14-1 Laboratory Reactor Loaded with Swine Wastes 102

19 Removal Efficiencies of Various Pollutional Parameters from Imhoff Cone Laboratory Reactors Loaded with Swine Waste 103

20 Uniformity of Raw Swine Waste During Agitation and Loading of Field Pilot-Scale Lagoons 108

21 Swine Waste Loading Rate of Field Pilot-Scale Units 109

22 Steady Supernatant Concentration of Field Pilot-Scale Lagoons Loaded at Various Rates with Swine Wastes 129

23 Liquid Concentration at Several Depths for a Field Pilot-Scale Lagoon Loaded with Swine Wastes at Four Times the Reference Rate 131

24 Dependence of Panel-Rated Odor Rank on Sampling Location and Loading Rate for Field Pilot-Scale Units with Swine Waste 134

25 Sludge Depth Determination for Anaerobic Swine Lagoons Loaded at Different Rates 135

LIST OF TABLES (Continued)

26	Removal Efficiencies (Equation 1) and Effluent Concentration of Various Parameters from Field Pilot-Scale Reactors Loaded with Swine Waste	137
27	Design Considerations for Naturally Aerobic Lagoons and Pilot-Scale Lagoon Performance	138
28	Comparison of Biochemical and Chemical Oxygen Demand of Various Field and Laboratory Anaerobic Reactors Loaded with Swine Waste	139
29	Oxidation-Reduction Potential Measurements at Mid-Depth in Field Pilot-Scale Anaerobic Swine Lagoons	141
30	Gas Composition from Field Pilot Units Receiving Different Aeration Intensity	152
31	Oxygen Mass Balance for Fixed Aerator Operating in Field Pilot-Scale Reactor Loaded Once Per Week at Two Times the Reference Rate for Swine Wastes	154
32	Average Supernatant Concentration Values (January-April 1974) for Farm-Scale and Field Pilot-Scale Lagoons Receiving Swine Waste	159
33	On-Farm Lagoon Supernatant Concentration Distribution in Vertical and Horizontal Directions (4/4/74)	160
34	Final Concentration and Batch Reaction Rate Constant for Laboratory Anaerobic Swine Reactors (14 1)	168
35	First-Order Reaction Rate Constants for Chemical Oxygen Demand (COD) in Anaerobic Swine Lagoon Units	179
36	First-Order Reaction Rate Constants for Total Organic Carbon (TOC) in Anaerobic Swine Lagoon Units	180
37	Mass Transfer Coefficients for Total Kjeldahl Nitrogen (TKN) as Lost from Anaerobic Swine Lagoon Units, Equation 26	186
38	Concentration and Areal Loading Rate for Swine Lagoon Effluent Reaching Plots Receiving High, Medium, and Low Rates of Application	199

LIST OF TABLES (Continued)

39 Comparison of Irrigated Swine Lagoon Effluent and Liquid Reaching Plot Surface - Night Irrigation 200

40 Comparison of Land Application Rate Based on Lagoon Concentration and Actual Material Reaching the Plant-Soil System 202

41 Bulk Density Variation with Depth in Coastal Plains Experimental Plots (Norfolk Sandy Loam) 203

42 Average Initial Soil Content in Upper 75 cm of Various Waste Parameters for Plots Receiving High, Medium, and Low Application Rates 204

43 Rainfall Runoff Volumes from Experimental Plots Evaluated in 1973 205

44 Effluent Irrigation Runoff Volumes from Experimental Plots Evaluated in 1973 206

45 Concentration of Rainfall Runoff from Experimental Plots Receiving Swine Lagoon Effluent 209

46 Dry Matter Yields (kg/ha.) and Percentage Dry Matter of Coastal Bermuda grass for First-Year Application of Three Loading Rates of Swine Lagoon Effluent (1973) 211

47 Mineral Concentrations of Coastal Bermuda grass (Average of Three Replications) for First-Year Application of Three Loading Rates of Swine Lagoon Effluent (1973) 213

48 Mineral Concentrations of Coastal Bermuda grass (Average of Three Replications) for First-Year Application of Three Loading Rates of Swine Lagoon Effluent (1973) 214

49 Crop Removal Rates for First Year of Swine Lagoon Effluent Application to Coastal Bermuda grass (1973) 215

50 In Vitro Dry Matter Disappearance (IVDMD) and Total Nitrogen Concentration of Coastal Bermuda grass Hays for First-Year Application of Three Loading Rates of Swine Lagoon Effluent, 1973, (Mean Values of 3 Replications) 217

LIST OF TABLES (Continued)

51 Animal Intake and Hay Composition for Coastal Bermuda grass for First-Year Application of Swine Lagoon Effluent, 1973 218

52 Soil Accumulation in Upper 75 cm Beneath Plots Receiving Swine Lagoon Effluent After One Season, September, 1973 221

53 Soil Accumulation in Upper 75 cm Beneath Plots Receiving Swine Lagoon Effluent After One Season, December, 1973 222

54 Overall Mass Balance for First-Year Application of Swine Lagoon Effluent at the High Rate to a Coastal Bermuda grass - Norfolk Soil Plot System (Average of Three Replicates) 239

55 Overall Mass Balance for First-Year Application of Swine Lagoon Effluent at Medium Rate to a Coastal Bermuda grass - Norfolk Soil Plot System (Average of Three Replicates) 240

56 Overall Mass Balance for First-Year Application of Swine Lagoon Effluent at the Low Rate to a Coastal Bermuda grass -Norfolk Soil Plot System (Average of Three Replicates) 241

57 Percentages of Various Waste Constituents Removed by the Major Plant-Soil System Pathways for the Coastal Bermuda-Coastal Plains Experiment Receiving One Season of Swine Lagoon Effluent 243

Acknowledgements

The continuous and enthusiastic support of the North Carolina Agricultural Experiment Station and Extension Service was fundamental for the expansion of the research objectives and goals of this project. The direction, encouragement, and perseverance of Mr. Lynn Shuyler, project officer, and associated EPA staff have been extremely helpful in the completion of this Environmental Protection Agency grant, number R802203.

Expressions of gratitude are in order for more individuals than can be reasonably expressed in an acknowledgement section because of the scope of this project in terms of interdisciplinary effort and magnitude of supportive assistance. At the risk of unintentionally overlooking most valuable and helpful inputs, the following contributions are noted by work unit and some key individuals.

At the University Unit 2 Research Farm, Mr. H. V. Marshall, Superintendent in Charge of University Research Farms, and Mr. R. J. Williams, Unit 2 Farm Superintendent; Dr. O. W. Robison, Dr. R. F. Behlow, and Dr. A. J. Clawson, Animal Science; and at the Central Crops Research Station, Mr. W. C. Allsbrook and Mr. W. R. Baker, Superintendents; Mr. J. R. Woodard and Dr. J. R. Jones of Animal Science are thanked. Cooperators from Soil Science included Dr. G. A. Cummings, Dr. B. L. Carlile, and Dr. J. W. Gilliam. Dr. J. C. Burns, Crop Science, and Dr. Lemuel Goode, Animal Science, were essential for the work on yield and nutritive value of experimental plot cover crop. Dr. R. W. Skaggs was most helpful with the soil-water considerations for the land irrigation work, and both Mr. L. B. Driggers and Dr. R. G. Holmes assisted in the total planning and operational analyses, as well as many other colleagues in Biological and Agricultural Engineering, and in particular Mr. R. B. Greene, Supervisor of the research shop, and his staff.

Special appreciation is expressed to Dr. G. A. Cummings, Soil Science, and Dr. R. E. Sneed, Irrigation Specialist, for their hard work in assisting with installation of field plots. Field plot operation and maintenance, as well as the analyses and interpretation of the soils data, were coordinated by Dr. G. A. Cummings. Dr. Burns coordinated plot crop activities in conjunction with the feeding trials conducted by Dr. Goode. The resources, continuous practical advice, and physical labor of Mr. H. V. Marshall and Mr. R. J. Williams at the research farm were superlative. Selective thanks also go to Dr. A. Stewart for swine management activities.

The continuous advice and stimulation of Dr. G. J. Kriz, Assistant Director of the Experiment Station, Mr. D. H. Howells, Director of the Water Resources Research Institute of the University of North Carolina, and especially Dr. F. J. Hassler, Department Head of Biological and Agricultural Engineering, in conjunction with the technical assistance of Dr. P. Westerman and Dr. J. C. Barker, departmental faculty members in agricultural waste management research and extension, served to reinforce and augment project activity.

The majority of the hard work in the field and laboratory was supervised by Mr. S. T. Britt, Mr. J. F. Koon, Ms. June Preston, and Mr. J. D. Olson, and executed by a well respected but anonymously diligent staff.

Gratitude is expressed for the dedication and associated graduate student activity of Mr. Howell, who was responsible for the lagoon work, and Mr. T. Miller for surface aeration work.

Brenda Butts and Jan Jackson are thanked for their patience and excellence in producing the final report.

SECTION I

CONCLUSIONS

A. LABORATORY SCALE LAGOONS

1. Supernatant concentrations were related to loading rate. At extremely heavy loading or about 0.21 m^3/45-kg hog, supernatant TOC, TKN, and orthophosphorus concentrations were approximately equal to raw waste values. Data for operation at 2.3 m^3/45-kg hog or more resulted in 90-95 percent removals of input COD, TOC, TKN, and o-PO_4-P.

2. Approximately 70 percent of the input TKN, TOC, and COD for laboratory batch or continuous loading was not recovered as output or accumulation due to organic stabilization and nitrogen volatilization.

3. Results for one- and 14-liter laboratory units loaded at frequencies between once/2 weeks and three times/week for units with 2.3 m^3 and 0.6 m^3/45-kg hog showed that loading frequency had little effect on:
    a. supernatant quality.
    b. sludge amounts and mass balances.

4. A slight reduction in supernatant quality resulted by using continuous loading as compared to batch loading when considering COD, TOC, and TKN at 2.3 m^3/45-kg hog or 0.9 kg COD/m^3/wk. Little difference was evidenced for orthophosphorus. At the heavier loading of 0.6 m^3/45-kg hog or 3.6 kg COD/m^3/wk, there did not appear to be any supernatant quality differences between once per week and continuous loading for COD, TOC, TKN, and o-PO_4-P.

5. Approximately the same amount of time (about 12 weeks) was required between start-up and steady-state conditions for batch type laboratory reactors seeded with lagoon sludge and supernatant when compared with those begun with tap water.

6. Response and achievement of steady-state times for laboratory and field lagoons were generally longest for TKN. COD concentration response was less rapid than TOC and was generally more variable as an indicator of supernatant quality, while minimal response for orthophosphorus was noted.

B. LABORATORY SCALE LAGOONS WITH DIFFERENT SLUDGE MANAGEMENT

1. Three sludge management reactors were studied: a) sludge removal 6-8 hours after loading, b) average sludge detention of 4-5 weeks, and c) accumulation of all settled material with an average sludge residence time of 10-15 weeks. There were no significant differences for supernatant concentrations of COD, TOC, TKN, and o-PO_4-P among these reactors loaded at 2.3 m^3/45-kg hog. Thus, it is concluded that the presence of a sludge layer and subsequent interfacial transport was less important in determining supernatant quality than biostabilization and other loss mechanisms ongoing in the supernatant.

2. Postulated reasons for similar supernatant concentrations regardless of sludge management were that the supernatant had a high level of microbial activity which with once-per-week loading was very probably underutilized. Thus, these microorganisms effectively used sludge by-products, as well as the raw waste input as substrate masking any differences in interfacial transfer between reactors with no sludge, controlled sludge, or accumulated sludge. Supernatant bacterial data supported these conclusions.

3. Sludge mass balance differences between laboratory reactors with no sludge or total solids removal and accumulated sludge or no solids removal were dramatic. About 40-50 percent of the COD, TOC, and TKN which settled initially in the no-sludge cones was ultimately stabilized in the accumulated sludge cones. This partially explains the slow rate of sludge buildup in actual lagoons. As expected, phosphorus compounds were conservative; and thus, the same percentage amounts were present in all alternative sludge management studies.

4. The percentage of input constituents remaining in the sludge for three laboratory experiment duration periods (19 to 56 weeks) was very similar indicating a steady-state decay level for accumulated bottom sludge. The percentage of swine waste input COD, TOC, and TKN which remained in the sludge zone was approximately 30 percent. Sludge buildup rates in laboratory reactors indicated that a lagoon would fill with sludge in about 1,000-3,000 days. Field experience had indicated that a slower buildup occurs; therefore, caution should be exercised in transferring laboratory sludge accumulation data to actual field conditions. Factors such as compaction under greater liquid head, soil incorporation, effluent carryover,

and long-term mixed culture biochemical stabilization could reduce field lagoon sludge buildup rates below that measured in shorter duration laboratory studies.

C. FIELD PILOT-SCALE UNAERATED LAGOONS

1. Lagoon supernatant concentrations for laboratory or field lagoons having 2.3 m^3/45-kg hog or more were found to be uniform with depth throughout the total supernatant.

2. Steady-state concentrations for the pilot-scale lagoons were higher than laboratory units at comparable loading rates.

3. Supernatant COD, TOC, TKN, and orthophosphorus concentrations were found to decrease in value as loading rate decreased or as the lagoon volume increased for both laboratory and field units. Supernatant TOC and TKN concentrations were directly proportional to the loading rate at about 2.3 m^3/45-kg hog or more.

4. The percentage of input COD, TOC, TKN, and orthophosphorus in the effluent of unaerated lagoons at 2.3 m^3/45-kg hog or more was very low. Correspondingly, 90 percent and often more than 95 percent removals were obtained. At higher loading rates, the phosphate and nitrogen removal became considerably lower. The nitrogen removal at a loading rate of 0.6 m^3/45-kg hog was only about 36-65 percent of the input; and thus, this type of lagoon would be more appropriate for nitrogen conservation.

5. After 120 weeks of operation, the three pilot-scale field units had a sludge buildup of approximately 12 percent of the waste input volume, whereas sludge buildups in laboratory units were about 25 to 30 percent of the waste input volume.

6. Sludge COD, TOC, o-PO_4-P, and TKN concentrations were similar for all laboratory and field experiments conducted. No conclusive evidence of concentration profiles within the well defined sludge zone were found. Sludge was generally 35,000 to 60,000 mg/l COD; 12,000 to 18,000 mg/l TOC; and 2,000 to 3,000 mg/l TKN. These sludge values are close to raw swine waste concentrations. Sludge orthophosphorus concentrations of 2,000 to 3,000 mg/l were 2 to 4 times the raw waste value indicating settling and accumulation of phosphorus which is a conservative element.

7. Detectable levels of dissolved oxygen near the lagoon surface were not consistently found except for units at 37 to 74 m^3/45-kg hog and the third lagoon in series in which the

initial unit had 2.3 m^3/45-kg hog. No dissolved oxygen was found at depths greater than 10 cm below the surface even for units at 37 and 74 m^3/45-kg hog which transcended design criteria for unaerated aerobic lagoons for swine waste. Hence, design criteria for unaerated aerobic lagoons were not supported by this study.

8. Based upon aperiodic field observation and odor panel rankings, it was concluded that there was a discernible odor threshold for swine waste lagoons loaded at approximately 9.2 to 18.4 m^3/45-kg hog. Odor was not manure-like nor was an odor always detectable for lagoons with more than 18.4 m^3/45-kg hog. For lagoons with less than 9.2 m^3/45-kg hog, odor was not always detectable, but when found it was characteristic of swine manure and hence was deemed offensive.

9. Individual consensus indicated that the frequency or probability of odor detection when visiting the site was 80 percent for the unit at 0.6 m^3/45-kg hog, 60 percent for 2.3 m^3/45-kg hog, 20 percent for 4.6 m^3/45-kg hog, and little odor for units with 9.2 m^3/45-kg hog or greater.

D. FIELD PILOT-SCALE AERATED LAGOONS

Results from aerated lagoon experiments were impacted by bottom scour resulting from the aerator-reactor size ratio employed. Therefore, the magnitude of the resultant conclusions are somewhat unique to the investigated reactor conditions.

1. Supernatant organic and nitrogen concentrations for aerated units without bulk phase dissolved oxygen are lower than similarly loaded unaerated units. No dissolved oxygen was found in the aerated units, even in the surface layers. Additionally, reduced odor potential existed for aerated units at the same loading intensity as similar unaerated reactors.

2. Supernatant COD and TOC concentrations increased with increased aeration rates from 37 to 120 watts and associated greater bottom scour, while TKN concentrations showed only a modest increase indicating that the greatest impact of surface aeration is on nitrogen reduction by ammonia volatilization.

3. Allowing a quiescent period after raw waste loading for settling (24 hours) did not result in improved supernatant quality for aeration at the 60-watt level.

4. Aeration strategy employed was to accomplish odor and scum control through complete surface agitation by horizontal pumpage which requires a minimum of 1 hp/93 m^2 (1 hp/1,000 ft^2) surface area for utilized equipment. This operation also results in substantial nitrogen reduction by ammonia volatilization.

5. Mass balance calculations indicated an oxygen transfer of 1.7-1.8 kg O_2/hr/kw or about 80 percent of manufacturer's rating of 2.1 kg O_2/hr/kw.

E. FARM SCALE LAGOON

1. The investigated farm-scale lagoon had lower effluent concentrations than comparatively loaded field pilot units. The explanation for these lower steady-state conditions for the farm scale lagoon may have included the daily loading frequency and the cyclic nature of the total waste load. Also, the overall loading increased slowly as the hog population built which would allow development of good biological populations. Additionally, because the housing unit was more open to the atmosphere than totally enclosed houses, there was added opportunity for waste degradation prior to lagoon input. Thus, growing unit configuration and waste management techniques can have significant impact on waste degradation prior to lagoon loading and thus influence the performance of treatment units.

2. Sampling of producer scale field lagoons at various locations verifies laboratory and pilot field conclusions that supernatant quality is relatively homogeneous. This uniformity of supernatant concentration for analyzed constituents in experimental units ranging in size from 1 liter to over 850 m^3 was an unexpected result. Calculations indicated that diffusion represented a minor contribution to supernatant uniformity. Daily temperature cycles and thus thermal induced currents were not considered as the principle explanation because supernatant uniformity also occurred with laboratory reactors in a constant temperature environment. Postulated mechanisms were a) high level of active biomass and b) mixing effects of microorganisms and liberated gas.

3. Supernatant TKN concentrations for pilot-scale and full scale lagoons evidenced an annual variation, about 250 mg/l for the spring-summer period and 350 mg/l for the fall-winter period. This difference in nitrogen concentration reflected the shift in equilibrium between ammonium ion and ammonia and the decreased volatilization associated with lower temperatures.

4. Sludge buildup for laboratory units loaded at 2.3 m^3/45-kg hog was from 15 to 35 percent of the lagoon volume per year.

Field pilot-scale units had a sludge buildup of 10 to 15 percent of lagoon volume per year at the same loading. Sludge buildup rates for producer-scale field units have not been as great because of long-term compaction and degradation. However, it was concluded that sludge buildup for lagoons loaded at about 2.3 m^3/45-kg hog would require cleanout at a 10-year interval or greater.

F. PREDICTIVE AND INTERPRETIVE RELATIONSHIPS FOR LAGOONS

1. The batch loading model developed to describe lagoon performance could predict the effect of periodic loading. The major disadvantage was that transient conditions which had an impact for longer than one loading period such as a change in loading concentration or volume could only be determined by a number of successive weekly calculations. This limitation prevented rapid prediction of steady-state conditions associated with lagoon management options.

2. Predicted steady-state supernatant concentrations for storage lagoons by the continuous modeling technique indicated that when the supernatant COD concentration was above 30,000 mg/l the lagoon was not functioning biologically.

3. On an overall basis, the use of an average reaction rate constant based on a continuous loading model as determined in the laboratory and temperature corrected or from a field experiment for a single loading rate gave a good approximate value for the supernatant COD and TOC concentrations. First-order rate constants for COD and TOC were 0.55 $week^{-1}$ for laboratory-scale ($T=25^\circ$ C) and 0.15 $week^{-1}$ for field-scale units. The prediction of supernatant TOC concentration was better than COD.

4. Reaction rate constants for COD and TOC removal calculated from laboratory data and adjusted to field temperatures predicted lagoon supernatant values that were somewhat higher than actual recorded data, indicating that the field units were slightly more efficient than laboratory reactors when put on the same temperature basis.

5. The internal consistency of first-order TKN mass transfer coefficients derived from the continuous loading model for various lagoon loading rates was better than first-order reaction constants for COD and TOC. Rate constants for COD and TOC varied by a factor of 3 while TKN removal constant values varied by less than a factor of 2 over the same loading

range, 2.3 to 74 m^3/45-kg hog. This consistency may be partly attributed to the physical mechanism for TKN removal (ammonia volatilization) as opposed to the microbial dependent stabilization of organics.

6. Developed models verified the slower supernatant TKN response to changed lagoon operation and that supernatant nitrogen levels were determined by surface area independent of volume. The larger the surface area-to-volume ratio the faster the approach to steady-state TKN conditions indicating a surface volatilization mechanism instead of a bulk reaction removal. This areal removal dependence for TKN was contrasted to the microbial base volumetric dependence for COD and TOC.

G. LAND APPLICATION OF SWINE WASTEWATER

1. Concentration data for irrigation of lagoon supernatant showed that for a lagoon loaded at 2.3 m^3/45-kg hog approximately 25 percent of the nitrogen and 10 percent of the COD are lost during night irrigation. This irrigation loss data cannot be directly extrapolated to larger farm-type sprinklers, but higher losses would be anticipated for daytime irrigation because of higher temperatures and wind velocities.

2. Preliminary runoff data for the first year application of 300, 600, and 1,200 kg of nitrogen/ha./year indicated that runoff volume was approximately 15 percent of the rainfall.

3. For COD application rates of 1,525, 3,050, and 6,100 kg/ha., the percentage loss in runoff decreased with increasing loading rate from 2.0 to 0.5 percent. Although there was a slightly greater rainfall runoff volume for the high nitrogen application plots, the liquid concentration of organics (COD) lost could not be directly correlated to waste application rate because neither the high nor low rate plots consistently yielded the greatest amount of COD runoff. Runoff concentration similarities implied that the effect of different loading rates was minimal and that the amount lost as a percentage of that applied decreased with an increasing loading rate.

4. Concentrations for direct irrigation runoff were roughly 50-80 percent of the irrigated wastewater levels; but within 0.3 to 1.5 m of the receiver plot, complete infiltration of irrigation runoff occurred.

5. Although irrigation runoff volumes were small compared to the total applied, waste constituent transport was significant when compared to rainfall runoff especially for the high nitrogen rate plots. The expected high concentration of pollutants in this liquid emphasized the need to preclude this type of runoff. However, continued long-term monitoring as sod develops more fully may show that these runoff volumes become significantly reduced.

6. Order of magnitude calculations indicated that less than 5 percent of all applied waste constituents appeared in rainfall runoff.

7. Sheep acceptability evaluations of Coastal Bermuda hay from the terminal swine waste irrigation plots indicated no evidence of reduced hay palatability. The hay intake per unit body weight was not significantly different for the effluent land loading rates evaluated although crude protein content of the hay increased with increased loading rate.

8. Waste plot Coastal Bermuda grass dry matter contents were lower at the 600 and 1,200 kg of nitrogen/ha./yr rates than for the 300 kg of nitrogen/ha./yr demonstrating the greater water uptake and top growth associated with excess nitrogen conditions. Comparison of the dry matter yield among the three effluent treatments demonstrated increased growth with increased effluent loading rate. However, use of kg of nitrogen/ha did not significantly increase dry matter yield over the 600 kg of nitrogen/ha./yr rate indicating the plateau region for response to nitrogen. The amount of N, P, and K applied at the highest rate was more than double the amounts found to produce maximum yields of Coastal Bermuda grass in North Carolina. In general, the increase in grass dry matter concentration of applied elements was significant between various application rates.

9. Summarizing the soil accumulation results after 1 year of application for the total 75 cm profile, four waste constituents, NO_3-N, K, Na, and Cl, were deduced to have increased significantly between low and high rate waste loading above the control or initial soil levels on an overall mass balance basis. The other soil parameters, TKN, Ca, Mg, P, Cu, Zn, Fe, and Mn, were not significantly affected by loading rate although some were at higher levels than control cores or had slightly elevated surface concentrations. Both Mg and Ca evidence a surface accumulation, but levels returned to control concentrations about 3 months after irrigation termination. This second group of constituents were either

not applied at high rates compared to initial levels, were not reliably detected, or were leached from the upper 75 cm of soil and hence were not recorded as constituents that accumulated in the soil profile.

10. Crop removals as a percentage of applied material increased as the effluent application decreased as was expected because plant requirements were below applied levels. The actual amount of various waste materials measured in the harvested crop increased by nearly twofold from the low to the medium rate and only slightly from the medium rate to the high application. Material unaccounted for by crop uptake, accumulated in the soil profile, or transported in runoff was about the same for the low and medium rate plots except for nitrogen which increased from 100 kg/ha. to 250 kg/ha. The high rate plots had nearly a twofold increase in unaccounted materials including nitrogen over the medium rate plots. Attributing these losses conclusively to leaching after this first-year study was not possible because the anticipated relative freedom of movement or mobility of these constituents was not verified. That is, K, Na, and Cl should have been much more mobile in the soil than Ca, Mg, or P. However, leaching losses as a percentage of the amount applied or initially present were not significantly greater for K, Na, and Cl as compared to P, Ca, and Mg. Thus, other factors yet unsubstantiated prevented indepth conclusions regarding mass balances or pathways for removal of waste constituents. Several years of data would be required to reduce the effect of annual variability of crop uptake and rainfall runoff as related to the total system mass balance.

SECTION II

RECOMMENDATIONS

A. ANALYTICAL TECHNIQUES

1. Results from the 15-minute and 2-hour digestion for the chemical oxygen demand test as outlined in Standard Methods show no statistical difference for all swine waste samples. Thus, this shortened procedure represents the most cost-effective manner to determine oxygen demand for waste characterization, aeration requirements and unit performance evaluations.

B. LAGOON TREATMENT

1. Animal waste is quite concentrated and contains all the microflora needed for adequate anaerobic stabilization. Therefore, seeding new lagoons to enhance treatment has marginal benefit in most cases. These recommendations do not, however, conflict with suggestions to provide waste dilution during lagoon start-up.

2. Engineered systems to control or remove settled solids to improve lagoon supernatant quality would not be warranted based upon recorded insignificant differences in supernatant quality due to sludge management techniques ranging from no solids removal to elimination of all solids attendant to no bottom sludge.

3. For maximum destructive pretreatment, it may be best to allow all solids to enter the primary lagoon rather than provide selective removal in view of the excellent bottom sludge stabilization.

4. Greater supernatant COD, TOC, and TKN reduction occurred for both laboratory and field units loaded on a continuous or nearly continuous basis at 2.3 m^3/45-kg hog or more. This type of waste input could be accomplished by a continuous manure pit overflow, frequent flushing, or daily scraping and cleaning.

5. The best parameter to evaluate lagoon operation and achievement of steady-state conditions is TKN because response time is longer than for TOC and COD and the importance of nitrogen content for terminal land application.

6. A sample taken at an intermediate depth is representative of average lagoon supernatant conditions.

7. Although approximately 90 percent removals of input COD, TOC, TKN, and orthophosphorus were achieved at a lagoon loading rate of 2.3 m^3/45-kg hog, effluent levels for these parameters were 1,500, 500, 400, and 40 mg/l, respectively. This resultant poor effluent quality emphasized justification for regulatory criteria specifying no-discharge for anaerobic swine lagoons.

8. Lagoon sizing criteria should be based upon the intended function of pretreatment in the overall waste management strategy. If odor or aesthetic nuisances are critical, then lagoon sizing based upon odor threshold of about 9 to 18 m^3/45-kg hog should be followed. If maximum nitrogen conservation is desired, then heavier loading rates such as 2.3 m^3/45-kg hog or less, even up to about 0.6 m^3/45-kg hog, could be used. Surface aeration may be employed in heavily loaded units to counteract odor potential and allow smaller sized lagoons. However, surface aeration results in increased nitrogen volatilization and thus is more appropriate as degradative pretreatment for land limited situations. Lagoon sizing will vary as a function of climatic conditions and moisture relationships. Regardless of management scheme, which may emphasize nitrogen conservation and thus heavy loading, or minimum nuisance conditions and correspondingly lighter loading, lagoons are to be regarded as pretreatment-storage devices and thus only one unit process in the overall waste management system pursuant to terminal land application.

9. Lagoon supernatant TKN, COD, and TOC concentrations can be estimated for lagoons sized at 2.3 m^3/45-kg hog or more by developed modeling techniques to give order-of-magnitude values for preliminary design of land application systems.

10. Design criteria for unaerated, aerobic lagoons are often counterproductive because bulk phase dissolved oxygen was not recorded for lagoons at commonly specified sizes of 37 to 74 m^3/45-kg hog and effluent quality was not suitable for discharge.

C. LAND APPLICATION

1. Land application of animal waste to pasture or hay crops

represents one of the most cost-effective terminal waste management systems. All field data collected indicate no hazard associated with applying waste at recommended fertilizer rates based upon nitrogen, phosphorus, and potassium for the moisture excess southeast. Actually, a margin of safety exists for short periods because when twice the recommended fertilization rate for Coastal Bermuda grass or 1200 kg of nitrogen/ha/year was added, little effect on crop quality and runoff transport was noted over the initial one-year period. However, soil nitrate, potassium, sodium, and chloride did show increases between the low and high-rate loadings and, in general, were above initial soil levels on an overall mass balance basis. Other soil parameters including copper and zinc were not significantly affected by the high loading rate and both magnesium and calcium which evidenced a surface accumulation returned to control concentrations about 3 months after irrigation termination. No evidence of reduced hay palatability in sheep feeding trials was recorded and intake per body weight was not significantly different among the loading rates studied, although the crude protein content increased with increased loading. Therefore, all data would indicate that virtually no environmental hazard results from the irrigation of animal wastewater at fertilizer rates over long-term periods, and that in fact, the environment can assimilate short-term, high-rate loads. However, indications are that long-term, high-rate applications would lead to soil accumulation, increased runoff transport, and excessive soil-water nitrate. (However, before final conclusions can be made, waste receiver plots would have to be studied for several years to reduce variabilities associated with start-up and annual cycles as well as to obtain data on a mature plot that would represent long-term, steady-state conditions.)

2. Runoff during or as a result of irrigation at excessive rates or antecedent moisture conditions must be avoided. A buffer zone can provide excellent attenuation by infiltration and overland flow stabilization and thus should always be provided to further reduce rainfall runoff transport.

3. Night irrigation substantially reduced nitrogen losses and mist nuisances without causing any noted liabilities, and thus should always be considered.

SECTION III

INTRODUCTION

GENERAL

Recommendations directing terminal land application of animal waste have been verified by the no-discharge criteria specified in the final Effluent Guidelines and Limitations for the Livestock Industry published in the February 14, 1974, Federal Register. Land requirements for the terminal application of animal waste are contingent upon the degree of pretreatment provided and the fate of waste materials applied to a particular soil-plant receiver system. Limiting waste materials of primary importance at present are total nitrogen, total salts, potassium, or feed additives depending upon relative concentrations in the applied waste and geoclimatic conditions.

The most common pretreatment-storage device for swine waste in the southeast is a single unaerated lagoon. Therefore, the thrust of this research project has been to define kinetics and mechanisms for waste material degradation or removal for various lagoon loading conditions in conjunction with efforts to define relationships between loading intensity and frequency, sludge accumulation, odor potential, and treatment performance.

Design, operational, and economic information for aerated lagoons have also become a high priority request as attention is being directed to this alternative method for odor reduction from these pretreatment-storage devices prior to terminal land application. Additionally, surface aeration can augment nitrogen removal for cases where sufficient land is not available to assimilate the nitrogen load associated with application of raw waste or even excess lagoon liquid.

The major goal of these studies was to develop design and operational criteria for pretreatment units and terminal land receiver plots that are responsive to particular management strategies, such as maximum component destruction or maximum nutrient conservation. Odor potential was a most important consideration for lagoons. Criteria for any land-based system must also take into account health and nuisance requirements, cover crop management, geoclimatic conditions, equipment, and producer preference in conjunction with environmental impact.

Ideally, recommendations would be developed to define loading and operational criteria for maximum nitrogen or organic conservation, with or without regard for odor control, that could be utilized for producers interested in this management strategy. Correspondingly, other producers could adopt criteria that would either exclusively or by selective compromise achieve goals desired for a particular management program.

Over-treatment of waste results in unnecessary and burdensome expense and work input, whereas inadequate treatment represents a misuse of facilities and a negligent effort. The importance of determining relationships between loading and operation characteristics of treatment facilities was readily apparent because many unaerated and aerated lagoons were being constructed by rule-of-thumb estimates based on many different and possibly irrelevant parameters. Correspondingly, research and field experience pursuant to design and operational criteria responsive to a particular waste management strategy and terminal disposal or utilization scheme represented a high priority work area.

PROJECT OBJECTIVES

The specific objectives of this research project outlined in the original proposal and pursued throughout the study period were:

1. To provide specific information on the performance of field pilot-scale lagoons and farm-scale systems for swine waste with the view of evaluating or refining the design criteria in the southeast region for:

    a. unaerated lagoon loading rates ranging from 1.15 cubic meter (cu m) to 73.6 cu m per 45-kilogram (kg) hog;

    b. two and three lagoon series systems consisting of unaerated facultative or aerobic lagoons following an initial anaerobic lagoon;

    c. surface aeration strategies for minimum lagoon oxygenation for odor control and increased nitrogen removal by ammonia volatilization and nitrification-denitrification in the aerated unit; and

d. land irrigation of liquid from a full-scale unaerated lagoon to Coastal Plains, Coastal Bermuda grass plots characteristic of the southeast.

2. To evaluate and correlate with contemporary standard analytical methods additional tests necessary for the development of sound criteria for evaluation and design of animal waste treatment facilities.

SCOPE AND PURPOSE

Field Pilot-Scale Lagoons

During the first portion of this study, a comparative experiment of the following unaerated lagoon treatments was performed based on a reference loading rate of 2.3 cu m of lagoon volume per 45-kg hog which was the proposed criterion for the region:

Unit 1 - four times reference loading
Unit 2 - reference loading
Unit 3 - 1/2 reference loading
Unit 4 - 1/4 reference loading
Unit 5 - 1/8 reference loading
Unit 6 - 1/16 reference loading
Unit 7 - 1/32 reference loading
Unit 8 - overflow from Unit 2
Unit 9 - overflow from Unit 8

This series of loading rates ranged from greater than any recommendations to lower than criteria for unaerated aerobic units. In addition, Units 2, 8, and 9 represented a series lagoon system. The recommendation for naturally aerobic lagoons was bracketed between Units 6 and 7 so the validity of recommendations for unaerated aerobic lagoons was tested. All lagoons were 3.5 meters (m) in diameter and 1.8 m deep, except for the second and third lagoons comprising the series system for Unit 2, which were 1.2 m deep.

Surface aeration by variable speed, 185-watt, fixed aerators was employed in two 3.5 m diameter and 1.8 m deep reactors. Relationships between loading intensity and aeration input were evaluated to determine minimum energy requirements for odor control. Operational strategies to increase ammonia volatilization and nitrification-denitrification in a single reactor operated without bulk phase oxygen excess were investigated pursuant to increased nitrogen removal prior to land application in limited areas.

Laboratory-Scale Lagoons

Model field unit investigations were augmented by laboratory studies with 14-liter (l) reactors and Imhoff cones to further elucidate operational parameters and basic mechanisms with the aid of controlled and definable conditions. Data derived from these laboratory reactors were most helpful in analyzing and evaluating performance of both the field full-scale and model reactors.

Farm-Scale Lagoons

The producer-scale lagoon used as a wastewater source for the land application studies was monitored in addition to other producer lagoons to document performance of typical farm-scale lagoons in the southeast. The lagoon at the land application study site was built in 1961 according to Midwest Plan Service recommendations of 0.12 cu m lagoon volume per kg hog live-weight. Waste was either washed or scraped daily from the solid concrete floors into a collection trough for lagoon input. After an identical housing unit and lagoon were added in 1971, the two lagoons were operated in series with all waste initially discharged to the original lagoon and overflow going to the new lagoon. Wastewater for the land application studies was irrigated from the initial lagoon. The swine research facility has cyclic population densities; and thus, waste lagoon inputs continuously vary with time at this site and at other farm-scale lagoons typical of actual producer operations. Data from these lagoons serve to evaluate predictive and interpretive relationships.

Land Application Studies

The land application investigations were conducted to determine the effects of various nitrogen loading rates for swine waste lagoon liquid on crop productivity and environmental quality. The three loading rates studied were 300, 600, and 1,200 kg of nitrogen/ha./year by the employment of three replicate plots for each application. The middle rate approximates the nitrogen requirements for optimum yield of Coastal Bermuda grass which was used as the assay crop. Data were collected to determine the amount of nitrogen which leaves the irrigated plots in rainfall runoff. The control area for soil accumulation comparisons was adjacent to the Coastal Bermuda pasture and received annual maintenance fertilization of 127 kg nitrogen/ha., 55 kg P/ha., and 127 kg K/ha.

Analytical Studies

Analytical techniques were evaluated throughout the duration of this study in an effort to either verify suitability of contemporary tests or develop more suitable procedures. Extensive experimentation to determine the best analysis for oxygen demand evaluation was conducted. Selective electrode and instrumental techniques were compared with contemporary wet chemical procedures for nitrogen species and chloride.

Material balances on conservative elements were routinely made to check techniques and augment laboratory quality control efforts. Procedures required for accurate characterization of sludge components for field and laboratory units pursuant to mass balance and mechanistic analyses were developed.

Technology Transfer

Factual information on the performance of swine waste lagoons in this area was conflicting when this project was proposed. Therefore, it was difficult to evaluate design criteria or make competent recommendations. Additionally, the waste load for a typical swine production unit was not adequately documented. Thus, this project was undertaken to obtain baseline data, determine lagoon performance, investigate basic mechanisms, and develop design and operational criteria responsive to desired unit and overall system management goals.

Results of this study have been used to develop technical papers and extension publications. Extension publications on waste characterization and management alternatives have served as basis for state-wide training sessions. Additionally, regional workshops on the treatment of agricultural waste pursuant to land application were held for state regulatory personnel and consulting engineers in the southeastern United States. Results and information derived from this research have set a basis for continued development and transfer of technical data at all user levels as opportunity and need direct.

SECTION IV

LITERATURE REVIEW

SWINE PRODUCTION TRENDS

Swine production has changed drastically in the United States in recent years. The unit where a small number of hogs were grown on open pasture has largely been replaced by a production site where large numbers are grown in confinement. While the number of producers has declined somewhat, the size of operations and the amount of investment have steadily increased. For example, in North Carolina in 1972 there were 72 percent fewer producers with 12 sows or less than there were in 1966, and during this same period, the number of producers with 100 sows or more increased by 450 percent (Jones[1]).

Production intensity of hogs at the national level usually follows cycles over a relatively short number of years that are responsive to market conditions. As of December 31, 1974, hogs and pigs on U.S. farms were estimated at 55.1 million head, ten percent less than a year earlier and seven percent below December 1, 1972, for the lowest December 1 since 1965 (NCDA[2]). The 14 states that make quarterly estimates, which include the ten Corn Belt states plus the southeastern states of North Carolina, Georgia, Kentucky and Texas, account for about 85 percent of this total.

These swine production changes and increased public concern for environmental quality magnified waste management problems. The Secretary of Agriculture in a 1969 report to the President of the United States emphasized that animal wastes exceed the waste from any other segment of our agricultural-industrial-commercial-domestic complex. As a result of a study on the role of animal wastes in agricultural land runoff, Robbins et al.[3] concluded that the direct discharge of untreated or partially pretreated swine waste was totally unacceptable and that land application is very effective in minimizing water pollution.

PROPERTIES OF SWINE WASTE

According to Muehling[4] manure properties have been classified primarily as physical, chemical, and biological. These properties may be affected by, at least, physiology of the animal (size, sex, breed, activity), the feed ration (digestability and the protein fiber content), and the environment (temperature and humidity). The quality of the feed influences the amount hogs eat, conversion efficiency, and ultimately the quantity and chemical composition of waste.

Copper is a required trace diet supplement in the range of 5-10 parts/million (ppm), and feed additive levels of 125 to 250 ppm are used by some producers. Taiganides[5] estimated that 80 percent of swine feed copper was excreted in the manure. Data of Arial[6] revealed about 80 percent carry-over of ingested copper, 70 percent of the zinc, and miniscule levels of antibiotic chlortetracycline due to rapid degradation.

The total amount of liquid manure to be handled is largely influenced by the type of operation and particularly wastage from waterers and foggers. Muehling[4] reported that the most generally accepted estimate of swine waste quantity has been five percent to eight percent of live weight/day consisting of about 15 percent dry matter. Humenik _et_ _al_.[7] in a literature review concluded that the most reliable weight and volume of raw waste/45-kg hog/day was 3.8 kg and 3.8 l, respectively.

Manure fertilizer and soil conditioner constituents have recently been investigated more extensively than any of the other chemical and biological characteristics, but considerable value variation for all constituents still exists in the literature. Values judged most reliable in a recent annotated literature review (Humenik _et_ _al_.[7]) were 0.32 kg chemical oxygen demand (COD), 0.13 kg five-day biochemical oxygen demand (BOD_5), 0.022 kg total nitrogen (TN), 0.063 kg total phosphorus, and 0.094 kg potassium/45-kg hog/day. The total organic carbon (TOC) was evaluated at 0.09 kg/45-kg hog/day (COD/TOC = 3.5). Based on literature references and calculations, it was judged that the raw waste COD and BOD_5 concentrations are about 80,000 milligrams/liter (mg/l) and 35,000 mg/l, respectively. The concentration of total solids (TS) in raw waste was evaluated to be about 80,000 mg/l for a corresponding moisture content about 92 percent.

Total waste volume in underfloor pits with partial or total slats and no water washing is approximately 3.8 l/day/45-kg hog, based upon data collected at N. C. State University (Humenik _et_ _al_.[7]) and other researchers (Scholz[8], Van Arsdall[9]). Therefore, the parameter concentrations for the waste in a storage pit with no overflow are about 1/2 the level of the defecated raw waste based on a total waste load of 3.8 l/45-kg hog/day.

OVERVIEW OF LAGOONS

Unaerated Aerobic Lagoons

Aerobic bacteria utilize waste as substrate, breaking down part of the organic portion into the more basic compounds of water and carbon dioxide in the presence of free oxygen. Some nitrogen is released to the atmosphere, but much of it is converted into nitrites and nitrates. However, the aerobic process is not 100 percent efficient in removing organic matter. According to Muehling[4] there is usually only 40 percent to 50 percent degradation of volatile solids (VS). McKinney[10] also states that there will be a large mass of solids in terms of generated biomass requiring disposal.

The major advantage of aerobic decomposition is that the entire process is essentially odorless. According to Dale[11] other benefits of aerobic decomposition are (a) partial decomposition of volatile (organic) solids into odorless gases, (b) destruction of most pathogenic organisms, (c) reduction in the pollutional characteristics of the wastes, and (d) concentration of minerals which may be more readily applied to the land.

Unfortunately, the use of unaerated aerobic lagoons for animal waste is generally not feasible because of the excessive surface area requirements. Hart and Turner[12] concluded that unaerated aerobic lagoons cannot be practically used because the high concentration of organics would require excessive amounts of dilution water to develop naturally aerobic conditions. McKinney[10] stated that the use of oxidation ponds for swine waste required far too much land area and that for such a large pond, mixing would be a problem because a 0.40 hectare (ha.) oxidation pond 1.2 m deep would be required for a 200-head hog operation. Most of the early livestock lagoons were expected to function as an aerobic lagoon but usually became anaerobic because loading was too heavy.

Eby[13,14] was one of the first researchers to make recommendations for the design, operation, and management of lagoons for disposal of livestock wastes. Design criteria were based on specifications for aerobic municipal sewage lagoons, calling for a shallow pond (.9 to 1.5 m deep) and allowing 125 to 500 pigs/ha. of lagoon depending on the climatic conditions. Eby[15] also characterized a properly functioning aerobic lagoon as one that is not offensive in appearance or odor.

Clark[16,17] concluded that lagoons for livestock waste must be aerobic if they are to be satisfactory for the producer and community. He recommended approximately one ha. of lagoon for each 680 hogs at 40° North latitude (about 14.7 square meters (sq m) of surface per hog). A loading variation of 15 percent/each 2½° variation in latitude was suggested. According to Muehling,[4] recent studies show that a lagoon will not remain aerobic at this loading without some method of restricting solids loading. Dale[18] recommended the volume of an aerobic lagoon for the Midwestern states as 0.31 cu m/kg of hog on feed. This was determined by using a BOD_5 loading of 50 kg/ha. of lagoon. He also concluded that aerobic lagoons must be cleaned after several years and weeds kept under control.

Unaerated Anaerobic Lagoons

Anaerobic decomposition has become one of the most common treatment alternatives for the swine producer. The anaerobic process usually results in undesirable odors, but the major benefit is the large flexibility to degrade organic material. Dornbush[19] has described the anaerobic process as follows: (a) In the initial stage, the complex materials such as carbohydrates, proteins, and fats are biologically converted and fragmented by hydrolysis and fermentation to the simpler organic end products including aldehydes and alcohols but principally fatty organic acids; and (b) during the second or methane formation stage the organic acids produced during the initial breakdown are converted by the methane-forming organisms to gaseous end products, principally methane and carbon dioxide. Waste stabilization or organic removal is directly proportional to the methane produced.

According to Muehling[4] the gas produced in a properly operating anaerobic digester is about 60 percent methane with the remainder of the gas being carbon dioxide and small quantities of various intermediate products. Muehling further judges that it is the intermediate products, less than one percent of the gas produced, which are responsible for odors.

Oswald[20] conducted extensive studies of lagoons in California and concluded that to develop an anaerobic lagoon that will be odor-free, the design must result in environmental conditions favorable to continuous methane formation.

Loehr[21] stated that in general the main purpose of anaerobic lagoons is the removal, destruction, and stabilization of organic matter and not water purification. He concluded that anaerobic lagoons offer considerable potential for handling and treating concentrated animal waste. Loehr[22] later concluded that anaerobic lagoons are practical only when used prior to further treatment and disposal.

Summarizing the status of livestock lagoons, Taiganides[23] stated that reports on the variable success of anaerobic lagoons reflect the variety of criteria and standards used to evaluate effectiveness. He felt that even though considerable research has been done in the past

15 years, it is still not clear how to design and operate an anaerobic lagoon so it will not occasionally give off undesirable odors.

Loading Rate Recommendations for Anaerobic Lagoons

Loading recommendations for anaerobic lagoons differ widely within the United States depending upon the loading parameter used and geoclimatic conditions. Loading recommendations range from about 1 to 24 cu m of lagoon volume/45-kg hog depending on the reference used and the particular part of the United States being considered (Muehling[4]).

Early recommendations given by Ricketts[24] and Jedele and Hansen[25] called for about 1.4 sq m of surface area/hog and a depth of 0.9 to 1.5 m. These lagoons were expected to function as municipal aerobic lagoons, but did not because of overloading.

Eby[26] divided the United States into regional areas and based recommendations on municipal lagoons which varied from 3,750 pigs/ha. of lagoon in the northern United States to 15,000 pigs/ha. of lagoon in the southern United States. The 1970 interim specifications for animal waste lagoons prepared by the Soil Conservation Service[27] were based on work by Eby but incorporated a 25-percent safety factor. Loading rates are specified as minimum surface area/animal for four different climatic zones within the United States. For the Southeast (Zone B), the loading rate is 1680 kg of BOD_5/surface ha. If the minimum specified depth of 1.8 m is utilized, this is equivalent to 2.2 cu m of lagoon volume/45-kg hog.

The latest engineering standard for disposal lagoons from the Soil Conservation Service[28] specifies 12.8, 9.6, 6.4, and 3.2 kg of VS/1,000 cu m of lagoon volume/day for the four climatic zones of the United States for swine. This is equivalent to about 1.9 cu m/45-kg hog for the Southeast (Zone B).

Many reserachers now feel that anaerobic lagoons should be designed on a volume basis rather than on surface area. Hart and Turner[12] varied their loading rates to determine the effect of different loading inputs on small test lagoons 1.22 m in diameter and 2.1 m deep in California. They compared lagoons loaded once/week at the rate of 3.5, 1.9, and 1.3 cu m of lagoon/45-kg hog and found relatively no difference in the appearance of the three lagoons. They felt that a loading rate of 1.9 cu m or even 1.3 cu m of lagoon/45-kg hog did not result in a particularly odorous lagoon and that 3.5 cu m/45-kg hog was very satisfactory for California. From these studies they concluded that anaerobic lagoons should be designed on a volumetric basis.

Willrich[29] reported studies with several small experimental microlagoons on the Iowa State University farm. He recommended a minimum of 0.124 cu m of lagoon/kg of hog and about 0.3 cu m/hog additional volume/year for sludge storage.

Based on their field investigations, Dornbush and Anderson[30] reported that the design of anaerobic lagoons should be on a volumetric basis. For South Dakota they suggested a satisfactory rule of thumb to be in the range of 3.7 to 4.8 cu m of lagoon/hog. Curtis[31] also studied existing lagoons in South Dakota and concluded that tentative design criteria should provide a volume of 2.1 to 2.8 cu m/hog.

A volume of 0.124 cu m/kg hog should be provided according to the Midwest Plan Service.[32] Also included is a recommendation for increased volume because swine wastes will cause sludge to accumulate in a lagoon at a rate of about 0.34 cu m/year/hog. Swine waste contains about 0.08 kg fixed or inert solids/45-kg hog/day or about 29 kg/year. Depending upon the sludge moisture content the corresponding volume will be proportionally larger than the 0.001 cu m which 1.0 kg of water occupies.

Lynn[33] studied the use of lagoons for treatment of hog wastes in South Carolina and compared the loading rates of one market-size hog per 1.7, 3.4, 5.1, and 6.8 cu m of lagoon. The 6.8 and 5.1 cu m lagoons were more efficient in removing BOD_5. The 1.7 and 3.4 cu m lagoons had highly offensive odors at times. From these studies he concluded that the quality of lagoon effluent was significantly affected by the loading rate and recommended a minimum of 5.1 cu m of lagoon/market-size hog and also 1.4 additional cu m of space to prolong cleaning time up to five years.

According to Taiganides,[23] design loading rates for anaerobic lagoons should be 0.016 to 0.238 kg of VS matter/day/cu m lagoon volume. From the standpoint of odor acceptability, the recommended loading rate is 0.029 kg of VS/day/cu m, which is equivalent to about 6.5 cu m lagoon volume/45-kg hog.

Miner[34] surveyed much of the available research and recommended a lagoon loading rate of 0.016 to 0.16 kg VS/cu m lagoon volume/day for the United States. This ten-fold range for the Midwestern climates 0.08 kg VS/cu m/day, which is equivalent to 3.54 cu m lagoon volume/45-kg hog, was recommended.

For Louisiana, Barr et al.[35] recommended that a swine lagoon should be 1.5 m deep, with 3.7 sq m surface area and 5.1 to 5.7 cu m capacity/45-kg animal.

Baldwin and Nordstedt[36] divided the state of Florida into two areas and recommended 2.38 cu m/45-kg hog for south Florida and 3.34 cu m/45-kg hog for north Florida.

Hermanson and Watson[37] recommended that a swine waste lagoon should be at least 2.4 m deep and have a capacity of 0.093 cu m/kg of hog. State of

Tennessee Criteria[38] also recommended that a swine lagoon should have a capacity of 0.093 cu m/kg of hog with a minimum acceptable liquid depth of 2.7 m.

An engineering practice for anaerobic lagoon design (ASAE[39]) is being developed for endorsement by the American Society of Agricultural Engineers which incorporates a loading adjustment factor for various geographical areas in the United States. This load factor ranges from 0.6 to 1.1, and criteria are based on 96 kg of VS/1,000 cu m/day. For a load factor of one, this corresponds to 2.26 cu m/45-kg hog. Recommended unaerated lagoon loading rates are summarized chronologically in Table 1 with the most recent listed last.

Table 1. ANAEROBIC LAGOON LOADING RATES

Reference	Loading recommendation	Cu m of lagoon /45 kg hog
Ricketts[24] and Jedele and Hansen[25]	1.4 sq m/hog--1.5 m deep (Missouri and Illinois)	1.3 to 2.1
Eby[26]	3,750 (far northern U.S.) to 15,000 (far southern U.S.) hogs/ha.; 1.5 to 3 m deep	1.5 m deep -- 1.1 to 4.1, 3.0 m deep -- 2.1 to 8.2
Dornbush and Anderson[30]	3.7 to 4.8 cu m/hog (South Dakota)	3.7 to 4.8
Hart and Turner[12]	3.5 cu m/45-kg hog (California)	3.5
Willrich[29]	Uniform loading--0.062 cu m/kg of hog Intermittent loading--0.057 cu m (Iowa)	2.8
Curtis[31]	2.1 to 2.8 cu m/hog (South Dakota)	2.1 to 2.8
Midwest Plan Service[32]	0.124 cu m/kg of hog (North Central Region)	5.6
Barr[35]	3.2 to 3.7 sq m/hog-- 1.5 m deep (Louisiana)	4.9 to 5.6

Table 1 (continued). ANAEROBIC LAGOON LOADING RATES

Reference	Loading recommendation	Cu m of lagoon /45-kg hog
Taiganides[23]	0.016 to 0.238 kg VS/day/cu m of lagoon (Variation for U. S.)	1.6 to 24.0
Hermanson and Watson[37]	0.093 cu m/kg of hog (Alabama)	4.2
Lynn[33]	5.1 cu m/market hog (South Carolina)	2.8
Miner[34]	0.016 to 0.16 kg VS/day cu m of lagoon (Variation for U. S.)	2.4 to 24.0 (3.5 for Midwest)
Soil Conservation Service[27]	0.00008, 0.00012, 0.00016 and 0.00036 surface ha/hog for climatic zones A, B, C, and D respectively--1.8m deep	1.5 to 6.6
Soil Conservation Service[28]	254, 193, 128, and 64 kg VS/1000 cu m of lagoon/day respectively for climatic zones A, B, C, and D	1.4 to 5.6
Baldwin and Nordstedt[36]	0.111 kg VS/day/cu m of lagoon (South Florida) 0.080 kg VS/day cu m of lagoon (North Florida)	2.4
State of Tennessee Dept. of Public Health[38]	0.093 cu m/kg of hog--2.7 m deep minimum	4.2
ASAE[39]	95.4 kg VS/1,000 cu m of lagoon/day times a correction factor of 0.6 to 1.1 (Variation for U. S.)	1.3 to 2.5

Nordstedt and Barth[40] noted that there are two loading rates which must be considered, the organic and hydraulic loading, and in most cases the organic loading rate will be the limiting factor. Correspondingly, the following conclusions were presented. First, a very wide range of anaerobic lagoon loading rates will produce satisfactory results. Second, the organic and hydraulic loading rates affect the rate of sludge accumulation and influence future sludge removal-maintenance costs. Third, the hydraulic loading rate directly affects costs for terminal land disposition.

Series Lagoons

The use of series lagoons has attracted attention; however, the efficiency of removal generally decreases as the number of lagoons increases. Nordstedt *et al.*[41] studied a multi-stage lagoon system for treatment of dairy waste and reported that BOD_5 reduction in the first, second, and third lagoons was 88.4 percent, 59.7 percent, and 22.6 percent, respectively.

Eby[15] in his early lagoon studies observed that when an existing lagoon was too small, the first step was to consider one or more connecting lagoons. He also concluded that two or more small lagoons in series are more efficient than one large lagoon with the same surface area since the first will be anaerobic and successive lagoons may be aerobic.

Lagoon Performance

While reviewing the state-of-the-art of anaerobic lagoons, Dornbush[19] concluded that the following areas need more research: (a) the thermal environment throughout lagoons, (b) the nature of the organics in both the lagoon influent and effluent, (c) the actual detention time of organics within the lagoon, and (d) the relative importance of sludge accumulations as a major source of nuisance odors.

Barsom[42] conducted an extensive review on the performance of municipal lagoons and discussed the following lagoon problems: (a) Poor effluent quality due to short-circuiting or reduction of designed detention time, (This can be due to poor design of inlet and outlet structures, thermal stratification, or hydraulic overloading), (b) presence of odors and other aesthetic failures due to production of hydrogen sulfide and growth of algae which remains suspended in effluent, and (c) water losses due to percolation from lagoon bottom into groundwater. He also found that sufficient data were not available for many lagoons on the quality and quantity of influent and effluent so that actual performance could be evaluated.

The Missouri Basin Engineering Health Council[43] conducted a review on the current state-of-the-art of wastewater lagoons. The following are some of the conclusions for anaerobic lagoons. (a) Anaerobic lagoons are useful in obtaining up to 80 percent BOD_5 reduction for concentrated organic wastes. (b) Anaerobic lagoons must be followed by aerobic treatment for high quality effluent. (c) Anaerobic lagoons have been most successful in treating meat packing wastes, (d) the future of all types of lagoons depends upon proper design and operation in relationship with the fundamental biochemistry of the microbes in the various systems.

Lagoon Loading Frequency

Early designers of municipal waste treatment systems recognized the need for very frequent loading in order to maintain a viable microbial population. For example, the Water Pollution Control Federation, Manual of Practice No. 11[44] states, "Organisms in a digester are most efficient when food is furnished in small quantities at frequent intervals."

McGhee[45] investigated the effect of intermittent sludge feeding and the consequent fluctuations in volatile acid concentration on digester performance. He concluded that better digestion could be achieved by regular and more frequent feedings.

Willrich[29] recommended 0.124 cu m of lagoon volume/kg of hog for intermittent loading, but felt that uniform loading was such an advantage that only 0.062 cu m of lagoon volume/kg of hog was needed. Miner[34] recommended a loading rate of 0.08 kg of VS/cu m of lagoon volume/day for continuous loading in the moderate midwestern climates.

Lagoon Aeration

Dale[46] and Loehr[47] in reviewing the status of animal waste treatment techniques emphasized that it is generally not feasible to design and operate aerated systems for direct effluent discharge to receiving waters. However, aeration for odor control and additional pretreatment prior to terminal land application has been supported as a technically feasible approach by many workers.

Aerobic treatment of swine waste is generally accomplished by an in-house oxidation ditch or an extramural lagoon with a floating surface aerator. Reports (Jones *et al.*[48]) on oxidation ditch performance have indicated BOD_5 reduction of about 90 percent and about 40 to 50 percent reduction of VS, along with complete odor elimination. Generally, gravity overflow to a lagoon must be provided because excess sludge and surplus water must be handled. Potential disadvantages of the in-house oxidation ditch are the impact on animal environment and energy requirements.

Design and operational criteria for aerated lagoons vary greatly in the literature dependent upon treatment strategy and equipment. Aeration recommendations for odor control range from satisfying the BOD_5 to 1/3 that value and aeration rates for complete treatment are reported to be from one to two times the daily BOD_5 input. Size requirement recommendations for aerated swine waste lagoons are from 0.0025 cu m to 0.062 cu m of lagoon volume/kg of hog.[4, 10, 48, 49]

Aeration can be employed to conserve nitrogen by conversion to nitrate or enhance nitrogen removal by ammonia volatilization and nitrification-denitrification depending upon unit management. Although biological denitrification generally requires sequential reactors for nitrogen oxidation to nitrite followed by an anaerobic unit for biological conversion of nitrate to nitrogen gas, nitrification-denitrification can be accomplished in a single reactor providing that both the oxidizing and reducing environment is present. An oxidation ditch which becomes anaerobic before the liquid recycles to the rotor can provide the aerobic-anaerobic sequential environment for denitrification (McKinney et al.[50]). A diphasic lagoon in which aeration is restricted to the surface area can also provide the aerobic-anaerobic interface required for biological denitrification (McCalf and Eddy[51]). These types of units require a delicate balance to achieve a nitrification-denitrification cycle for continuous or batch generation of nitrates and then subsequent conversion to nitrogen gas.

Lagoon Evaluation by Oxidation-Reduction Potential (ORP) Measurements

The ORP has been used in anaerobic systems to measure the degree of reduced conditions. A definite relationship exists between ORP and the aerobic-anaerobic condition of wastewater. E_{cal} is the ORP measured with a platinum electrode and a saturated calomel electrode, whereas E_h stands for measurements with bright platinum electrodes corrected to coincide with a standard hydrogen electrode. Microorganisms present will also be influenced by reactor ORP, and thus corresponding metabolic end products. Microbes operate in an E_{cal} range of +400 to -200 millivolts (mv) with anaerobes in a range of +50 to -400 mv and facultative bacteria in the range of +50 to -100 mv.[52]

Luddington[53] was one of the first to use ORP to control the amount of aeration employed in investigating odor threshold between aerobic and anaerobic treatments of liquid chicken manure. VS reduction, hydrogen sulphide production, and time after termination of aeration before hydrogen sulphide production for different ORP levels were studied.

Converse et al.[54] reported that the E_h potential varied from +400mv for aerobic to -250mv for highly anaerobic liquid waste treatments. Odor was found to increase dramatically below a threshold level of -50mv to -100mv. Relationships between odor and ORP were suggested as the most reasonable way to predict nuisance potential of an anaerobic treatment unit.

OVERVIEW OF LAND APPLICATION

Characterization of Constituents

A prediction of the effects of land disposal of animal wastes on soil properties and plant growth requires a foreknowledge of waste composition and receiver system characteristics. Generally, the composition range for waste constituents is so great that analysis of the specific residue is an absolute necessity before land application judgments or recommendations can be competently made.

Nitrogen

Nitrogen has received primary attention in judging the effects and, thus, allowable rates for land application or disposal of manure. Ammonia and organic nitrogen can be easily transformed by soil microorganisms to nitrate-nitrogen. Nitrate-nitrogen leaches easily through soil because it is an anion that has low sorptive capabilities and does not form insoluble precipitates. Excess nitrate can contribute to the stimulation of algal blooms and present potential health hazards in potable water supplies if concentrations exceed 10mg/l as nitrogen.

Several researchers have measured increases in total soil nitrogen after heavy application of beef waste and dairy-manure slurries. However, applications of animal waste will generally not increase steady-state soil nitrogen unless large quantities are continuously applied.[55, 56]

The accumulation and movement of nitrate-nitrogen in soils resulting from animal waste applications have been investigated by many workers. Mineralization of organic nitrogen into nitrate is most rapid during the first year following application and steadily declines in subsequent years. The decay series concept of nitrogen mineralization developed by Pratt *et al.*[57] describes this declining rate of nitrate-nitrogen production with time. These rate relationships for various manures can be used to estimate the amount of nitrate-nitrogen that will then become available for plant uptake or leaching into groundwater.

Nitrate-nitrogen in excess of crop needs or root sorptive capabilities is generally leached to lower soil zones. In some cases little if any nitrate movement was recorded even when large quantities of waste were applied. Much of this variability can be explained by differences in soil-water relationships. Soils that are well drained usually have a greater potential for nitrate movement and for applications of animal waste. Soils with restricted drainage will usually have a greater potential for nitrate transport because of insufficient leaching volume or anaerobic conditions which can lower nitrification and augment denitrification potentials. Therefore, nitrate generation and movement in soil profiles is governed by many factors requiring detailed and coordinated evaluation.

Nitrogen losses occur during land application and after deposition on the plant-soil receiver system. Kolliker and Miner[58] reported an unaccountable nitrogen loss of 2,307 kg/ha. in soil receiving anaerobic lagoon effluent by sprinkler irrigation. Olsen _et al_.[59] found that 20 to 76 percent of the nitrogen added to soil by dairy manure was lost through volatilization. Wallingford[60] and Meek _et al_.[61] measured unaccountable nitrogen losses ranging from 6.7 to 100 percent for soils receiving beef feedlot manure. These losses were attributed to denitrification and illustrate that denitrification can significantly lower the potential for nitrate leaching after land disposal of manure. However, caution must be exercised so that assumed nitrogen reduction by denitrification does not lead to excessive and thus, negligent land loading criteria.

Phosphorus

Verifications of the fact that phosphates are immobilized in most soils are abundant in the literature. Phosphorus transport is effectively restricted by incorporation of manure into the soil, and thus, erosion control is generally sufficient to protect water quality.

Inorganic Salts

Animal waste can improve soil fertility by the addition of inorganic salts, such as potassium, calcium, and magnesium. However, excessive accumulations of these salts and sodium result in increased salinity and thus, reduced fertility. The form of the ion and regional moisture conditions greatly affect the accumulation and movement of these constituents in a plant-soil receiver system. Generally, salt buildup as a result of even heavy manure applications does not reduce soil fertility or impede infiltration in the humid southeast and thus does not control application rates.

Heavy Metals and Trace Elements

Concern has developed that land-applied swine waste could be toxic to plant growth or grazing animals because of feed copper additions up to 250 ppm as a dietary supplement. Research on plant and soil accumulation of copper under various geoclimatic conditions for applications characteristic of feed additive levels of 125 ppm or soil ammendment applications up to 3.4 kg/ha./yr have shown from little effect (Hedges _et al_.[62] and Chaney[63]) to toxic conditions in cover grass (Humenik[64]).

Runoff Quantity and Quality

Miner and Willrich[65] concluded several years ago that "although runoff from feeding areas confining animals other than cattle may be expected to be high in organic matter, no data are currently available concerning these sources." Research directed at collecting data or developing models to access pollutional potential of runoff from land areas which have been used for terminal disposal of swine waste has just recently been initiated. Early work by Robbins *et al.*[66] showed that the pollutional potential of runoff from watersheds where swine waste was land spread, hogs were on drylot, and even where swine had stream access was similar to the natural pollutional load on streams draining agricultural lands devoid of farm animals. Mass balances for a watershed with 200 sows on a 1.2 ha. drylot plus wastes from 300 confined hogs spread on 2 ha. show that .69 percent, 1.66 percent, and 3 percent of the defecated BOD5, TOC, and total nitrogen, respectively, were present in the stream draining the studied watershed. Their conclusion included that even in cases where disposal sites are poorly located or swine grown on drylot, the amount of pollutants (natural plus animal waste) that reach receiving streams were less than 10 percent of the raw waste deposited in the watershed.

McCaskey *et al.*[67] evaluated runoff from grassland to which three rates of dairy manure were applied by irrigation, tank wagon, and dry spreading. Runoff data variations were attributed to either the type of waste, rate of application, or differences in soil character and vegetation. For some plots the amount of pollutant runoff was the same as for the controlled plots. Thus, few conclusive and quantitative deductions were drawn from this study.

Additional information about runoff as a diffuse source can only be inferred from beef feedlot runoff which represents a probable upper limit and hydrological studies of sediment, pesticide, and fertilizer transport. Upper estimates on the faction of waste transported in rainfall runoff from beef feedlots is less than 10 percent of the defecated load.[68, 69, 70, 71] Madden and Dornbush[70] concluded that potentially only 5 percent of the total beef waste generated would leave a feedlot in surface runoff, and this could be reduced to less than 2 percent if minimum detention facilities, diversion of foreign drainage, and reduction of runoff velocities were provided.

Concentration ranges for runoff from unpaved cattle feedlots are: COD from about 1,300 to 8,247 mg/l to 10,900 - 286,000 mg/l and nitrate from 0-17 mg/l to 0-31/mg/l (Gilbertson *et al.*[69]). Total nitrogen ranges from 50 to 540 mg/l (Miner *et al.*[68]) to 1,500 to 10,000 mg/l (Gilbertson *et al.*[69]). Robbins *et al.*[66] data showed similar stream concentrations for watersheds which had animals on drylot or pastures and were also used for terminal waste disposal as the control watershed of 0.1-70 mg/l BOD_5, 1-140 mg/l TOC, 1,012 mg/l ammonia plus organic nitrogen, 0.1-9.9 mg/l nitrate, and 0.1-17 mg/l orthophosphate ($o\text{-}PO_4\text{-}P$).

It is clear from the preceding summary that additional research is required to secure representative order of magnitude values for rainfall runoff quantity and quality. These data have become more urgent as attention is currently being directed to non-point source impacts on water quality. Any universal relationship to define quantity and quality of runoff from terminal application plots is not now possible because of the many unique and unpredictable factors involved. Regional geoclimatic conditions which profoundly affect runoff and solids transport very considerably. Additional work on handling methods, land management, cover crops, and environmental impact are necessary to expedite implementation of land application techniques which are most effective to achieve the no discharge goal for the livestock industry. Conjunctively, such data would provide competent direction for developing non-point source criteria as it pertains to runoff from areas utilized for terminal application of animal waste according to best recommended practices.

SECTION V

LAGOON STUDIES

SAMPLING AND ANALYTICAL PROCEDURES

Sample Collection

Liquid samples from the model laboratory reactors and the Imhoff cones were taken at mid-depth by using a pipette and then refrigerated. This method was satisfactory except for one very heavily loaded unit in which hindered settling and sludge buildup were pronounced. This reactor was subsequently sampled with an enlarged tip pipette 2-4 cm below the liquid surface.

Liquid samples from the field pilot-scale lagoons were taken at mid-depth in order to avoid collecting scum and surface algal growth. Sampling was accomplished by means of the APHA-type sampler recommended in Standard Methods[72] for collection of Dissolved Oxygen (DO), BOD_5, and other samples from ponds. Samples were then refrigerated at approximately 4° C until the specified analyses were performed.

A simple device constructed for collecting sludge samples from lagoons consisted of a 1.25 cm I.D. aluminum tube with a 90° bend approximately 15 cm from one end. To collect sludge samples, a stopper was placed in the end of the tube with the 90° bend. The tube was then submerged to the desired depth and the stopper removed from the bottom of the tube my means of a cord to allow sample entrance. The tube was then stoppered at the top and removed from the lagoon. After withdrawal the stopper was removed and the sludge sample poured into a sample bottle.

Samples were also taken from several on-farm lagoons. In some cases, "grab samples" were taken as far out as one could reach at the surface with a long-handled dipper. In other cases, samples were taken from a boat with the APHA-type sampler.

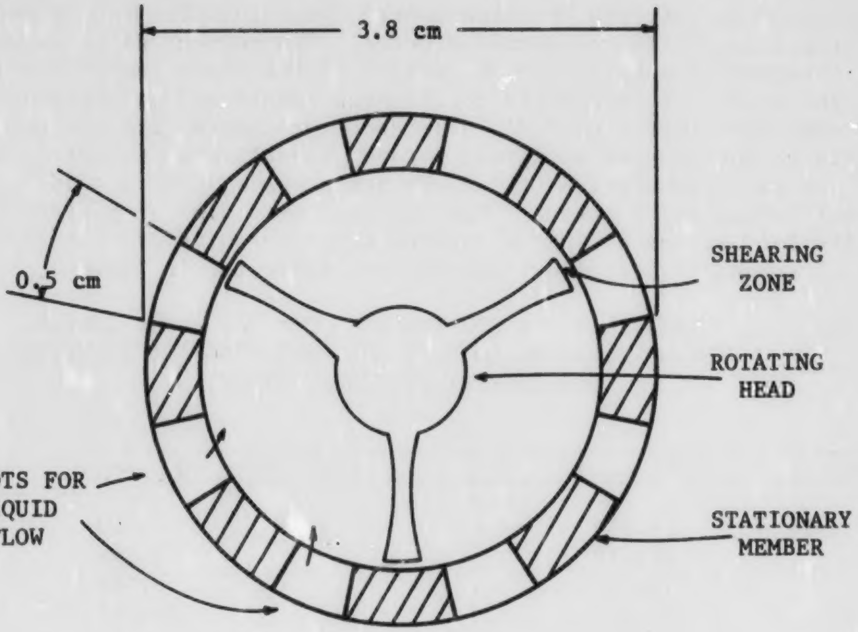
Sample Preparation

When necessary the samples from the laboratory reactors, Imhoff Cones, and field lagoons were diluted on a volumetric basis in order to bring the concentration of the particular parameter involved within the range of the analysis being performed. It was necessary to blend concentrated samples with large particulate matter such as raw waste and sludge. A high-speed blender with a shear-type head design, Figure 1, was used for 2 minutes at 18,000 rpm to reduce the size of suspended solids. Particle size reduction is very important when using instrumental analyses such as for total organic carbon where a syringe with a small orfice is used for sample measurement and injection. This prevents screening out of large particles and assures a more representative sample. Measured parameter variations for characteristic blended and unblended samples shown in Table 2 indicates that blending did not alter sample concentrations but only made handling more reliable.

Table 2. REPRESENTATIVE SUMMARY OF VARIOUS PARAMETER CONCENTRATIONS FOR BLENDED AND UNBLENDED SAMPLES

Multiple or Fraction of Reference Rate	Parameter	Concentration, mg/l Blended	Concentration, mg/l Unblended
4	COD	3,372	3,686
1	COD	1,396	1,412
1/2	COD	831	831
4	TOC	1,050	1,150
1	TOC	310	325
1/2	TOC	195	215
4	NH3	1,187	1,268

A more rigorous procedure was used for raw waste samples. These samples were weighed initially because it is extremely difficult to pipette a correct volume of unblended raw swine waste or sludge. The sample bottle including the sample was weighed on an analytical balance to the nearest tenth of a gram. Then the sample was placed in a 500-ml volumetric flask, followed by washing out the sample bottle with distilled water and adding enough distilled water to bring the flask up to volume. The contents of the flask were then placed in the high-speed, shear-type blender and blended at 18,000 rpm for approximately


3.8 cm
0.5 cm
SHEARING ZONE
ROTATING HEAD
SLOTS FOR LIQUID FLOW
STATIONARY MEMBER

TOP VIEW OF BLENDING HEAD

Figure 1. Schematic of shear-type blender head located inside blending container utilized for raw waste sample preparation, stainless steel construction.

2 minutes. The blender contents were then washed into a 1,000-ml volumetric flask with distilled water and brought to the correct volume. The diluted sample was then placed in a 1,000-ml Erlenmeyer flask and agitated with a magnetic stirrer because it was observed that mixing under similar conditions was incomplete in a volumetric flask. A 50-ml aliquot was then transferred with an enlarged tip volumetric pipette, to a 500-ml volumetric flask and brought to correct volume with distilled water. The contents of this flask were then placed into a 600-ml breaker and agitated with a magnetic stirrer. A portion was then transferred back into the sample bottle by using a large tip volumetric pipette. The percent dilution was then obtained by subtracting the weight of the empty sample bottle from the weight of the sample bottle plus sample and multiplying by the correction factor of 0.01. The above procedure gave the best results of the several different methods investigated to obtain the most accurate description of the raw swine waste used to load lagoons and all laboratory reactors. The expected precision of analytical results for raw waste sample replicates prepared using this procedure on four, successive, identical samples are indicated in Table 3.

Table 3. VARIABILITY OF COD ANALYSES FOR RAW WASTE SAMPLES USING SHEAR BLENDER, SAMPLE WEIGHING AND DILUTION FOR THIS EXPERIMENTAL STUDY.

Date	COD, mg/l	Date	COD, mg/l
2/15/74	59,860	2/18/74	67,263
	61,112		65,054
	60,084		57,666
	65,322		58,243

Analytical Procedures For Samples

Analyses performed on all samples were generally done according to procedures described in Standard Methods[72] except for some minor modifications described herein. All analyses described were not necessarily performed on every sample but tests performed on a particular sample were chosen to accomplish the study objectives.

Chemical Oxygen Demand (COD) -

The COD of all samples was obtained by using the procedure outlined in Standard Methods[72] for a 10-ml sample size with the modification that the 2-hour digestion time was reduced to 15 minutes. The validity of this modification for animal wastewater samples had been verified by the work of Overcash, et al.[73]

Total Organic Carbon (TOC) -

The carbon content of all samples was obtained with a Beckman Model 915 TOC Analyzer. The amount of total carbon was determined by injecting a microsample (20 ul) with a syringe into a 950°-C catalytic (Cobalt-impregnated, asbestos packing) combustion tube. The sample was then vaporized and the carbonaceous material completely oxidized to carbon dioxide and water in the presence of a cobalt catalyst. Zero grade carrier gas transported the generated carbon dioxide to this infrared analyzer for measurement. The carbon dioxide detected was directly proportional to the total carbon of the sample. The actual concentration was determined from the peak recorded on a strip chart, which was compared to a calibration curve.

Inorganic carbon was determined by injecting an identical microsample into a 150°-C combustion tube that contained quartz chips wetted with 85 percent phosphoric acid. This temperature was below the value at which organic matter oxidizes. All inorganic carbon was converted to carbon dioxide which was measured by the infrared analyzer. Inorganic carbon valves were then determined by comparing the peak recorded on a strip chart to a calibration curve. The sample TOC was then the difference between the total carbon and total inorganic carbon.

Biochemical Oxygen Demand (BOD$_5$) -

Several investigators (Clark[17], Humenik and Overcash[74], Busch[75]) have reported the inappropriateness of using the BOD$_5$ test to characterize animal wastes. For this reason primary reliance was placed on TOC and COD values. However, a number of BOD$_5$ values were obtained for correlation purposes. Most BOD tests were five-day, 20°-C unseeded, determinations according to procedures outlined in Standard Methods.[72] Pond water was used as dilution water for a few samples.

Ammonia and Organic Nitrogen (NH_3-N and O-N) -

Ammonia concentrations for many of the samples were determined by the Kjeldahl distillation procedure outlined in Standard Methods[72] for concentrated waste. Ammonia was collected in indicating boric acid solution and the amount determined by titration with dilute (.02 N) sulfuric acid. During the course of the study an Orion model 95-10 ammonia electrode was purchased and correlation of the ammonia values for these two methods proved that results were very similar, Figure 2. Organic nitrogen concentrations were usually obtained by the difference between total Kjeldahl and nitrogen (TKN) and ammonia values. These correlations were continued and after a year, the electrode method became unreliable. Electrode poisoning was postulated as the reason

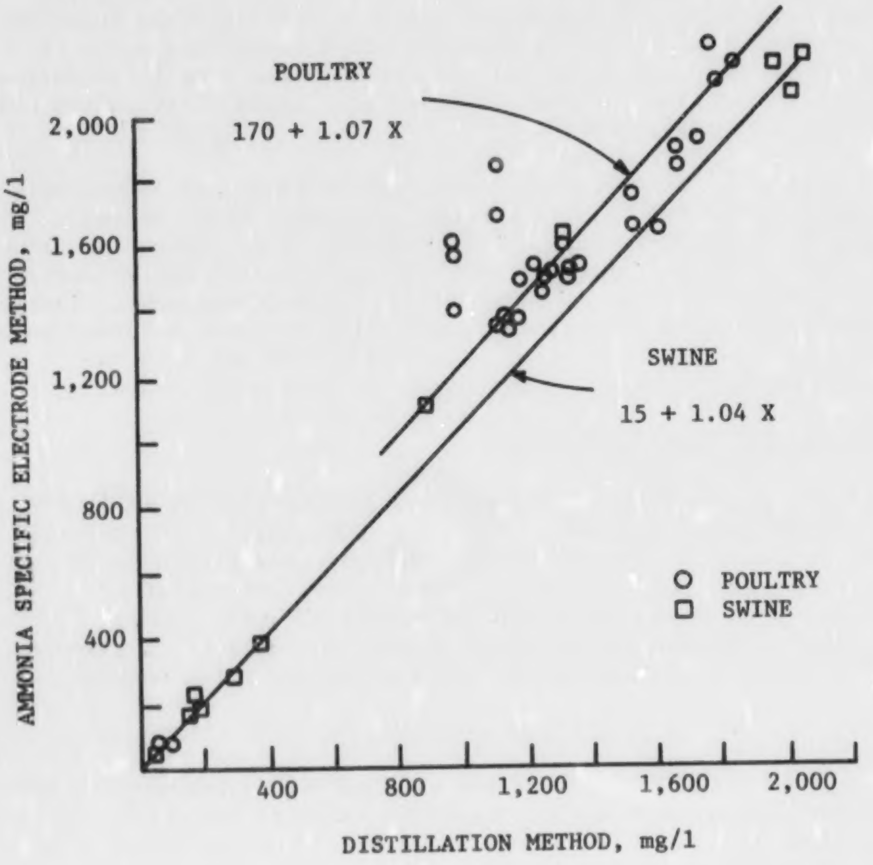


Figure 2. Comparison of ammonia analysis by ion specific electrode and standard distillation techniques for swine and poultry waste.

for reduced electrode dependability, Overcash et al.[73] After breakdown of the direct correspondence of the two tests, only the standard distillation was used.

Total Kjeldahl Nitrogen (TKN) -

Total kjeldahl nitrogen, the sum of the free ammonia plus organic nitrogen compounds was determined according to recommendations in Standard Methods[72] for concentrated waste. Procedures for test efficiency improvement were made frequently, Overcash et al.[73]

Orthophosphate (o-PO_4-P) -

The orthophosphate concentration of all samples was obtained by using the stannous chloride method as outlined in Standard Methods.[72]

Total Phosphate (t-PO_4-P) -

Verification was made early in the study that the total phosphate concentration was approximately equal to the orthophosphate concentration in virtually all samples except raw waste and sludge. Therefore, in most cases only orthophosphate values were obtained. When total phosphate concentrations were determined the per-sulfate digestion and stannous chloride method outlined in Standard Methods[72] were used.

Bacteria Densities -

Total coliform and fecal coliform densities were determined for a select number of samples, by employing the membrane filter technique (Taylor et al.[76]). Total coliform (TC) counts were made using M-Endo medium and incubation at 35° C for 20 hours (Kabler and Clark[77]). Fecal coliform (FC) determinations were made using M-FC broth and incubation at 44° C for 24 hours (Geldreich et al.[78]). Values were reported as colonies/100 ml.

Dissolved Oxygen (DO) -

Periodic dissolved oxygen checks were made of the liquid profile in the pilot field lagoons. A Weston-Stack dissolved oxygen meter equipped with an A-10 D.O. probe and a motorized sampler for submergence was used and calibrated against standards before and during each test period.

pH Measurements -

Frequent checks were made of the pH in the lab reactors and the pilot field lagoons. Determinations were made with a Corning Model 7 pH meter and a Fisher Standard combination electrode.

DEFINITION OF REFERENCE LOADING RATE

At the initiation of the anaerobic lagoon studies, a reference loading rate was established as a basis for comparison. This reference rate was developed on a per time and per volume of reactor basis to allow several size-scales of experimental devices. In an effort to operate in the range of common producer usage, the loading rates of several state and government agencies were consulted.

Units for the reference lagoon loading were chosen to be cubic meters of reactor volume per 45-kg hog, which by using the waste per week for a 45-kg hog could be converted to waste quantity per week per cubic meter of lagoon volume. The reference rate was chosen to be 2.3 m^3 volume per 45-kg hog which approximated the Soil Conservation Service recommendation for lagoons. The chemical oxygen demand was chosen as the basis for reactor loading and where feasible, the raw waste concentration was held constant at a level characteristic of swine operations. This concentration was 40,000 mg COD/l which was roughly equivalent to the raw waste of a 45-kg hog in a volume of manure, urine, and normal wash water of 7.5 liters per 45-kg hog per day.

Combining swine waste characterization with reactor volume requirements, various parametric means of defining the reference loading rate were determined to compare to other loading rates which have appeared in the literature, Table 4.

In the experimental plan of this study, various multiples or fractions of the reference rate were used so that it would be easy to calculate the actual loading rates by a multiplicative factor of the reference rate. The term reference rate referred only to the average amount of waste per unit reactor volume, m^3, and per unit time, week. It did not imply that the frequency of loading was once per week although per week appears in the units of reference loading. The frequency of loading varied with the experiments conducted.

SWINE WASTE CHARACTERIZATION FOR EXPERIMENTAL STUDIES

Included as an integral part of the lagoon pretreatment and land application investigations was the effect of the swine housing or production unit upon the raw waste load generated. The waste used to load laboratory and field pilot-scale experiments was from partially slatted houses (25 percent slats) with two pits per house and 16 pens per pit. The pigs maintained in these houses were characteristic of a finishing operation with constant purchasing and marketing to

Table 4. REFERENCE LOADING RATE UTILIZED IN ANAEROBIC LAGOON EXPERIMENTS EXPRESSED IN UNITS COMMONLY REPORTED

Equivalent Expressions for Reference Rate	
Metric System	English System
2.3 m^3 per 45-kg hog	80 ft^3 per 100-lb hog
24 m^3 raw waste per week per 1,000 m^3 reactor volume (at 7.5 l per 45-kg hog per day)	24 ft^3 raw waste per week per 1,000 ft^3 reactor volume (at 2 gal per 100-lb hog per day)
0.91 kg COD per week per m^3 reactor volume	58 lb COD per week per 1,000 ft^3 reactor volume
0.82 kg TS week per m^3 reactor volume	52 lb TS per week per 1,000 ft^3 reactor volume
0.67 kg VS per week per m^3 reactor volume	43 lb VS per week per 1,000 ft^3 reactor volume
960 kg BOD_5 per day per ka of surface area	860 lb BOD_5 per day per acre of surface area

maintain relatively constant liveweight. Production unit management was directed to achieve the goal of minimizing water usage to reduce waste volume. Hence, scraping for sanitation and thermostatically-activated fans and foggers were used so that when the temperature was above the comfort level the foggers operated 2 minutes out of every 10 minutes.

Generally pigs were maintained over three pits at a time, so that at least two pits had sufficient liveweight for the experiments underway. These two pits were dumped alternate weeks so that the waste in each pit was collected over a two-week period. All pits were connected via underground 25 cm pipe to a flume and a flow splitter. Usually no flow splitter was used so all the waste from a pit went to the 7,500-l mixing tank used to load the experimental lagoons. Prior to opening the pit flap valve and releasing pit contents, the liquid depth at the middle of each pit length was measured. If the pit volume was greater than experimental needs, the flow splitter was adjusted to divert a fraction of the waste to the on-farm lagoon. A flume and stage recorder were also installed so that total flow or waste volume could be determined.

Total pit emptying took considerable time because final slurry drainage was very slow. When emptying was complete, the solids level was measured at the middle of each pit length. If there was no flow splitting, the height of liquid in the mixing tank was measured to verify volume drained.

After each pit was emptied approximately 2,000 l of precharge water was added to reduce manure adhesion to the pit floor. Over the length of these experiments, it was observed that when such precharging was practiced, a pit slurry with no discernible settled or packed solids was characteristic. However, after draining a bottom solids layer remained indicating that the floor slope was not sufficient to maintain an adequate cleaning velocity. Nevertheless, it was observed that over many weeks this solids layer did not build and was resuspended when the pit precharge was added. Thus when a steady filling and draining pattern was established, easy evaluation of the characteristic swine waste load was possible.

After the swine waste entered the mixing tank, it was agitated for 15 to 30 minutes and then a representative sample was taken for analysis and loading of laboratory units. After the analyses were performed, the amount of water needed to dilute to approximately 40,000 mg COD/l was added. Mean data for raw waste analyses and diluted waste input for study units are listed in Table 5. In addition swine feces were collected and mixed with water to give a waste concentration of approximately 40,000 mg COD/l for certain laboratory studies. At various times, feces and urine have been analyzed for various parameters separately. This broad range of raw waste samples allows a more complete evaluation of swine waste and slurry from a slatted floor-manure pit production unit.

Two types of swine waste evaluations were derived from this study. The first was the quantities per 45-kg hog per day of waste volume, organic load (COD and TOC), phosphorus, and total Kjeldahl nitrogen (TKN) for an underfloor pit system. Secondly, the ratios of various parameters were analyzed. This second evaluation was less subject to the considerable variations often encountered in quantifying the generated waste. These parameter ratios also allowed expansion of data limited to one or two parameters to better characterize waste loads. Additionally, these parameter ratios could be used as a tool for analytical quality control.

Table 5. MEAN CONCENTRATIONS OF RAW SWINE WASTE AS USED FOR INPUT TO LABORATORY AND FIELD PILOT-SCALE EXPERIMENTS

Experiment	Parameter Concentration, mg/l			
	COD	TOC	TKN	o-PO_4-P
First Imhoff cones	31,000	9,000	1,800	500
Second Imhoff cones	40,000	12,600	2,800	---
Laboratory 14-l reactors	34,000	11,000	2,300	700
Field pilot-scale units 11/73-5/74	40,000	13,500	3,100	600
Mean raw waste concentration 3/73-5/74 before dilution	74,000	21,000	4,600	1,000

The total generated waste volume was determined by two methods. One was to measure the change in pit liquid height each week as gallons of input. The second was to measure the total volume drained from a pit with appropriate substraction of the precharge volume. From these two methods, the waste volume for a unit with a manure pit below partially slatted floors where manure is scraped and minimal water used was determined to be between 3.8 and 5.7 liters per 45-kg hog per day. This was close to the waste volume for feces plus urine of 3.0 to 3.8 liters per 45-kg hog per day as extensively documented in the literature (Overcash, et al.[79]).

The produce of the drained pit volume and constituent concentration yielded the waste generation data presented in Table 6 in conjunction with the valve judged most reliable in a recent literature review (Humenik et al.[7]). All chemical parameters determined for the waste at this unit were lower than the reference literature values.

Table 6. WASTE GENERATION FROM UNDER SLAT PIT RECEIVING SWINE WASTE

Parameter	Waste Amount, kg/d/45-kg hog 9/9/74-12/31/74	1/1/75-3/31/75	Literature values for fresh swine wastes
H_2O	3.5	4.2	3.8
TKN	0.017	0.019	0.022
o-PO_4-P	0.0035	0.0038	---
t-PO_4-P using ortho:total=.7	0.0050	0.0054	0.0064
COD	0.28	0.28	0.32
TOC	0.080	---	0.091

The ratios of various waste constituents were calculated, for the various sources of raw waste, raw waste diluted to about 40,000 mg COD/1, and feces plus water, Table 7. The COD:TOC, NH_3-N:TKN, and the o-PO_4-P:t-PO_4-P ratios have an upper theoretical numerical value. The COD:TOC ratio as defined in Standard Methods[72] has an upper limit of 5.3 which would indicate the most reduced organic carbon compound, methane, and a lower limit of 0 representing the most oxidized organic carbon compound, carbon dioxide. In this study, the COD:TOC ratio fluctuated around 3-3.5 but occasionally values above the upper theoretical limit of 5.3 were recorded indicating analytical or sampling errors. Literature value ratios of 5.3 or more were considered suspicious and not included for comparison in Table 6.

The fraction of the total nitrogen load which was in the more readily available ammonia (ammonia or ammonium ion) form was approximately 55 percent. The ortho: total phosphorus ratio indicated the fraction which was loosely bound and for raw swine waste this was about 70 percent. Thus a relatively large portion of the nitrogen and phosphorus in swine wastes was in the readily available form.

Table 7. CHEMICAL PARAMETER RATIOS OF VARIOUS SOURCES OF SWINE WASTE

Source	Ratio				
	COD: TOC	TKN: TOC	NH_3: TKN	o-PO_4-P: TKN	o-PO_4-P: t-PO_4-P
Agitated contents of gutter receiving once/day scraping	2.8	0.22	-	-	-
Underslat pit emptied once/two weeks-aliquot collected after emptying and mixing	3.9	0.27	0.52	0.21	0.72
Underslat pit contents emptied once/two weeks and diluted to approximately 40,000 mg COD/l	3.5	0.31	0.51	0.26	0.83
Fresh feces mixed with water to approximately 40,000 mg COD/l	2.6	0.18	-	0.24	-

In routine analyses of swine waste as well as a number of other characteristic samples, it was useful to have a range of acceptable values to screen for errors. Absolute constituent concentrations could fluctuate and still be acceptable for evaluations conducted because concentrations of raw waste often changed due to dilutional effects. Thus the ratio of concentrations and not the concentration itself was deemed a better analytical error screening tool. Ratios of the four most used parameters, COD, TOC, TKN, and o-PO_4-P, (Table 7), would indicate errors in any constituent such as TKN because the COD:TOC ratio would be in an acceptable range but the TKN:TOC and TKN:COD would be outside the range indicating the need for TKN reanalysis. Similar arguments could be made for other parameter errors. When two errors may cancel then reliance of the O-PO_4:TKN and other ratios was needed. This proved to be a useful first screening test even though it was not foolproof when several analytical errors in one sample were made. When several errors were indicated a complete rerun was instituted.

LABORATORY SCALE EXPERIMENTS

Imhoff Cones

Loading Frequency and Sludge Management Study-

Two sets of one-liter Imhoff cones with three cones per set were begun as the first experimental series. The differences among the three cones in a given set were in the management of the sludge which settled from the raw swine waste input. These operational differences were designed to indicate the magnitude of settling for various waste constituents and interfacial transfers between sludge and supernatant.

For the first set of three cones the loading frequency was once per week, an interval utilized in most of the laboratory and field experiments. The loading rate was the reference level corresponding to 2.3 m^3 of lagoon volume per 45-kg hog. Thus for these cone reactors the input was 25 ml of raw swine waste at a controlled concentration of 40,000 mg COD/l.

The first cone was managed such that after the weekly raw waste loading the settled solids were drained from the bottom through a stopcock. Thus except for the 6 to 8 hours required for initial settling this reactor operated with no sludge hence the designation 1NS1 (reference or unity loading, no sludge, one load per week). A second cone was loaded as the first but only enough sludge was drained to maintain about a 12-cm bottom sludge blanket. This scheme allowed interfacial contact between the supernatant and a controlled amount of settled material which represented the interfacial area or upper layer of the total sludge blanket. The designation for the second cone is 1CS1 (reference load, controlled sludge, one load per week). Finally the third cone, loaded as the previous two, was allowed to accumulate sludge. This cone served as a control or simulator of usual lagoon management and was designated 1AS1 (reference load, accumulated sludge, one load per week).

The second set of cones was different from the first in that the same reference waste input was added but at a frequency of three times per week. Thus 8.3 ml of raw swine waste were added on Monday, Wednesday, and Friday. Sludge management was the same as outlined for the first set of cones. The cone designations were 1NS3, 1CS3, and 1AS3. These cone experiments are depicted in Figure 3.

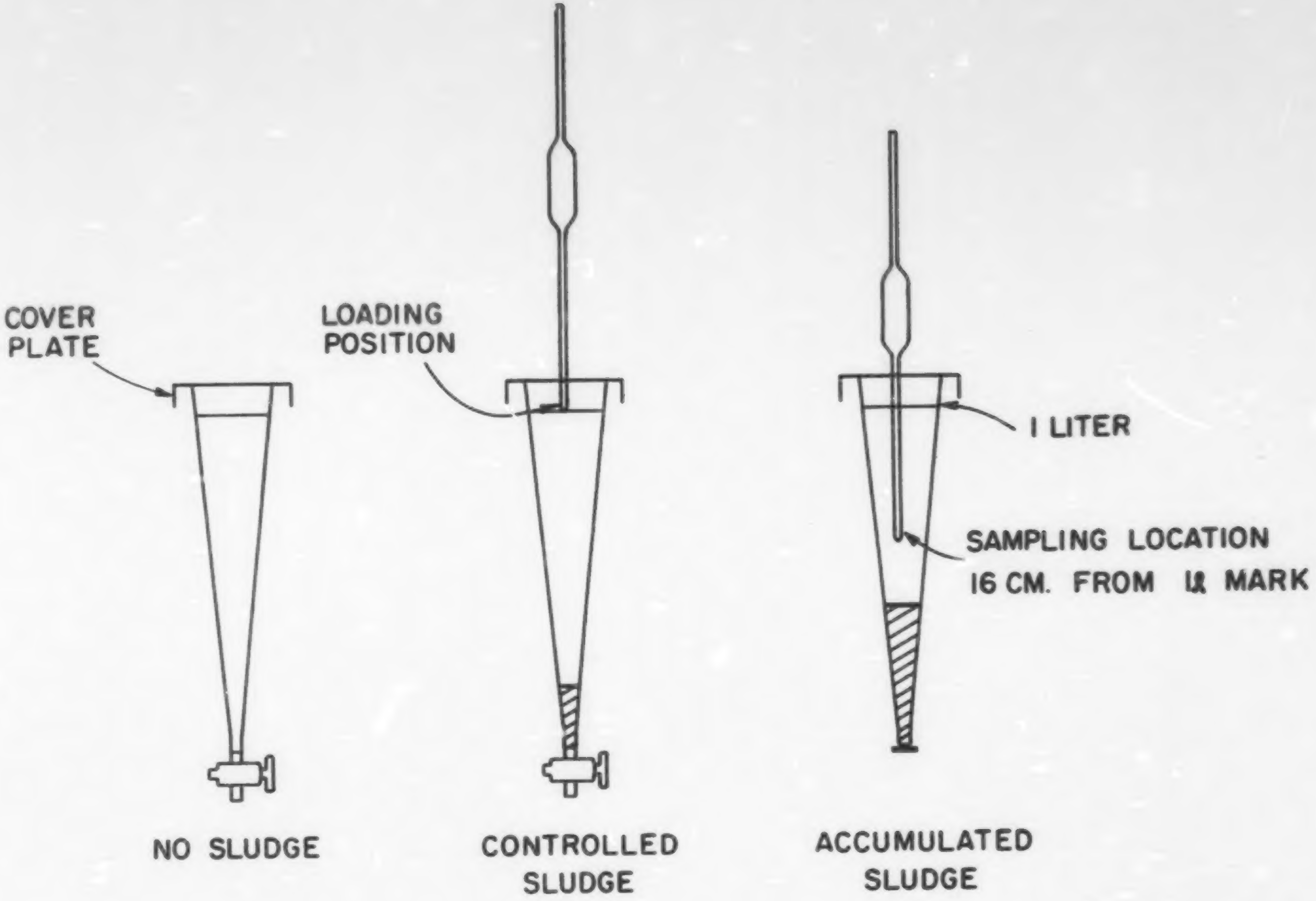

COVER PLATE
LOADING POSITION
1 LITER
SAMPLING LOCATION
16 CM. FROM 1ℓ MARK
NO SLUDGE
CONTROLLED SLUDGE
ACCUMULATED SLUDGE

Figure 3. Schematic of sludge management experiment with one-liter Imhoff cones loaded with swine waste.

Procedurally, the cones were filled with 990 ml of supernatant from a field lagoon. The four cones 1CS1, 1AS1, 1CS3, and 1AS3 received 10 ml of sludge from the same field lagoon. The two no-sludge cones received an additional 10 ml of field lagoon supernatant so that all reactors began with 1 liter of material. The use of lagoon supernatant and sludge was to provide an inoculum of microorganisms in both reactor phases. Loosely fitted cover plates were put over each cone to reduce evaporation losses.

Prior to each loading event, whether once or three times per week, a 20-ml sample of the supernatant was taken with a pipette at the 250-ml level from each cone. To evaluate the various processes present in an anaerobic lagoon, several parameters were monitored. Organic stabilization was indicated by changes in COD and TOC. The breakdown and subsequent losses of nitrogen were very important because nitrogen is generally the constituent in animal waste which limits terminal land application. Hence total Kjeldahl nitrogen (TKN) was measured and phosphorus, being a conservative element, was analyzed to check mass balance experiments. Usually orthophosphorus (o-PO_4-P) was determined because a high percentage of the total phosphorus was found to be orthophosphorus and because of the greater simplicity and speed of the ortho test.

The raw waste was added by gently releasing the pipette input onto the liquid surface at the center of each cone (Figure 3). After 6 to 8 hours, the settled solids were drained from the no-sludge cones as previously described. Controlled sludge units were drained of sludge periodically because of difficulty in clearly seeing the sludge height. Sludge sample volumes and COD, TOC, TKN, and o-PO_4-P concentrations were determined. The cover plates on each cone were not completely successful in preventing evaporation so the volume of the reactors decreased during the experiment. The final volumes are given in Appendix A1 along with all of the sample and sludge analyses. The change in volume was taken into consideration in data analyses.

Concentrations of four waste constituents in the supernatant of the two cone sets are shown in Figures 4-11. Steady-state supernatant concentrations were reached after eight to twelve weeks, and the experiment was terminated after about nineteen weeks. The slight increase in parameter concentrations near the end of the experiment was due to evaporative losses. The supernatant was removed from each cone and the volume and constituent concentrations determined. Then the sludge was removed, with volume and concentrations being measured. Finally, the cone walls were washed and this cleanout liquid was evaluated. With these termination measurements, the feed and initial charge measurements, and the volume and concentration of all the samples removed, mass balances for TOC, COD, TKN, and o-PO_4-P were performed. The amounts of each parameter and the percentages of raw waste input which were recovered as settled material or sludge are listed in Table 8. The

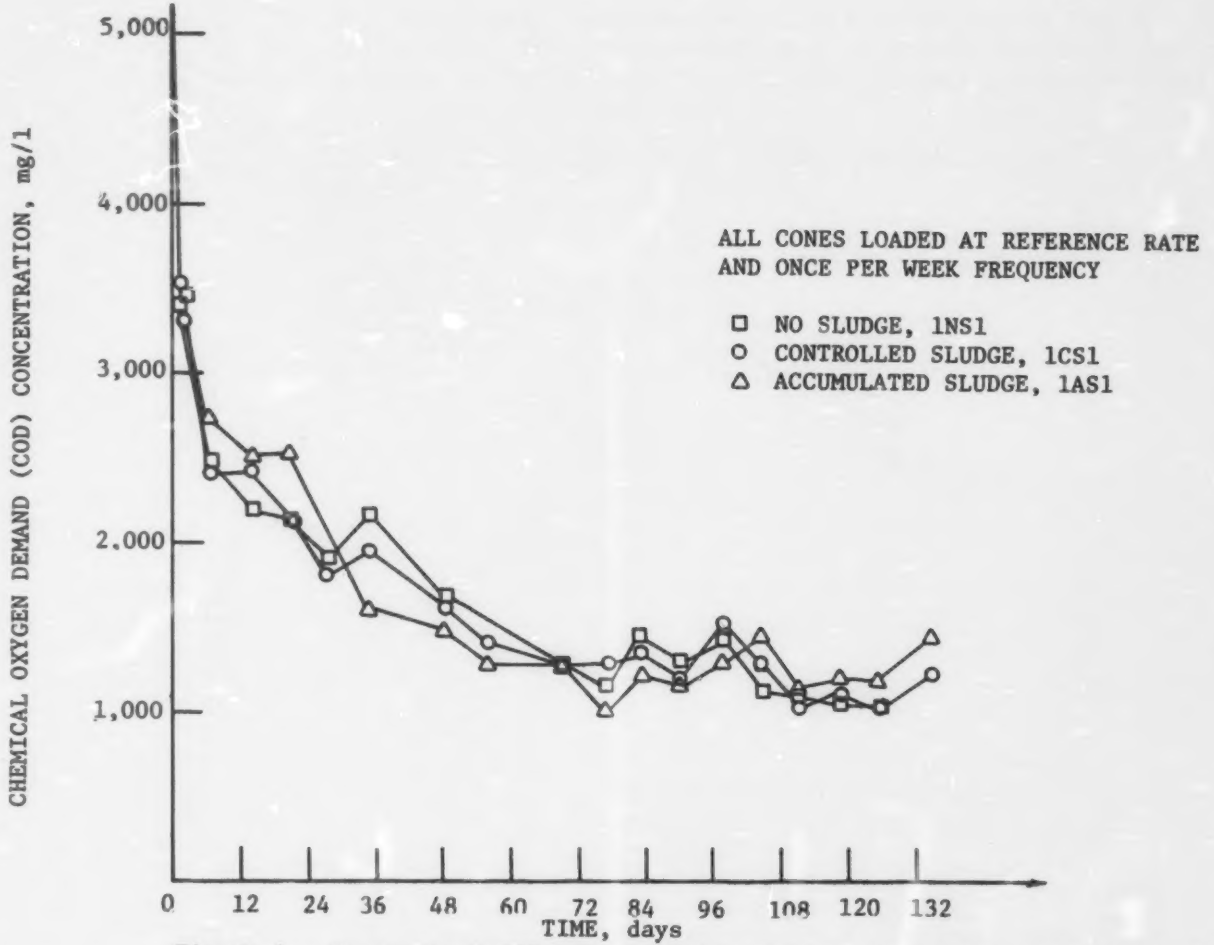


Figure 4. Supernatant COD concentration changes in Imhoff cones begun with swine waste lagoon supernatant with or without sludge as inoculum and loaded with raw swine waste (first experimental set).

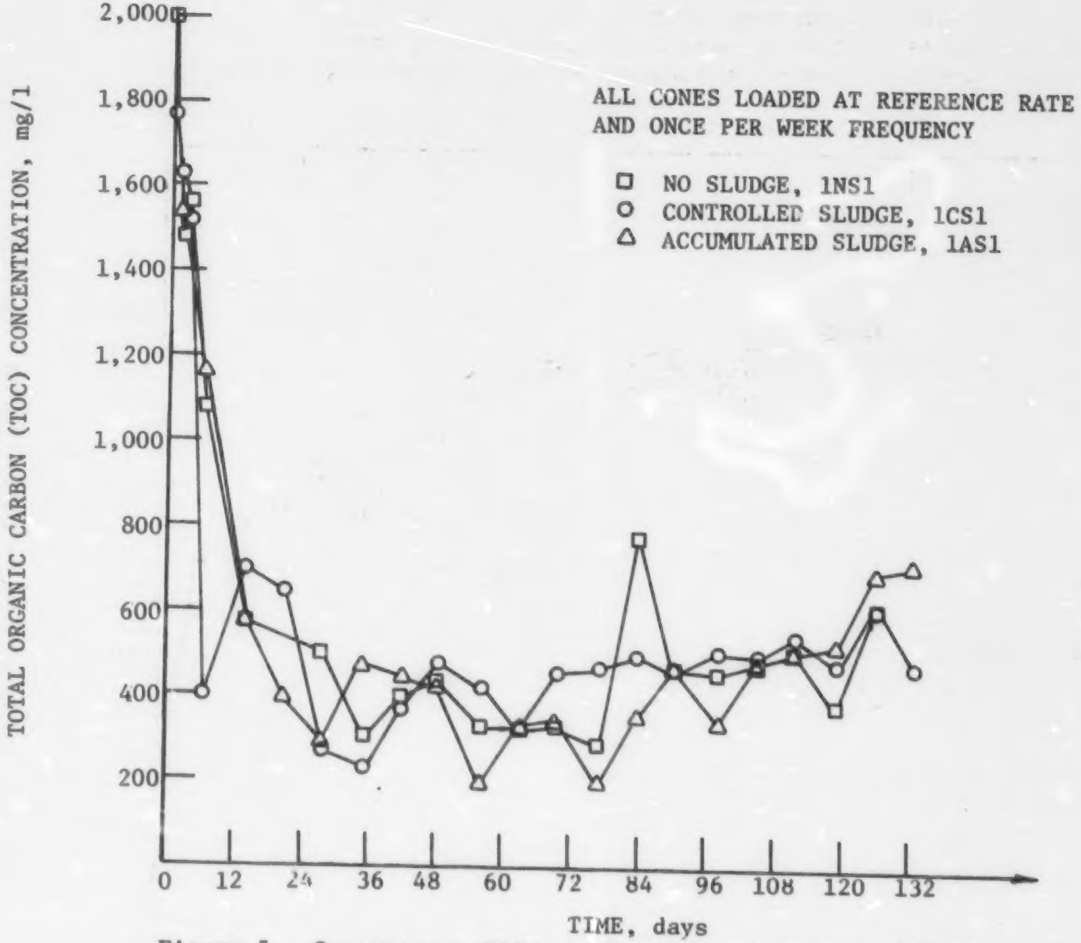


Figure 5. Supernatant TOC concentration changes in Imhoff cones begun with swine waste lagoon supernatant with or without sludge as inoculum and loaded with raw swine waste (first experimental set).

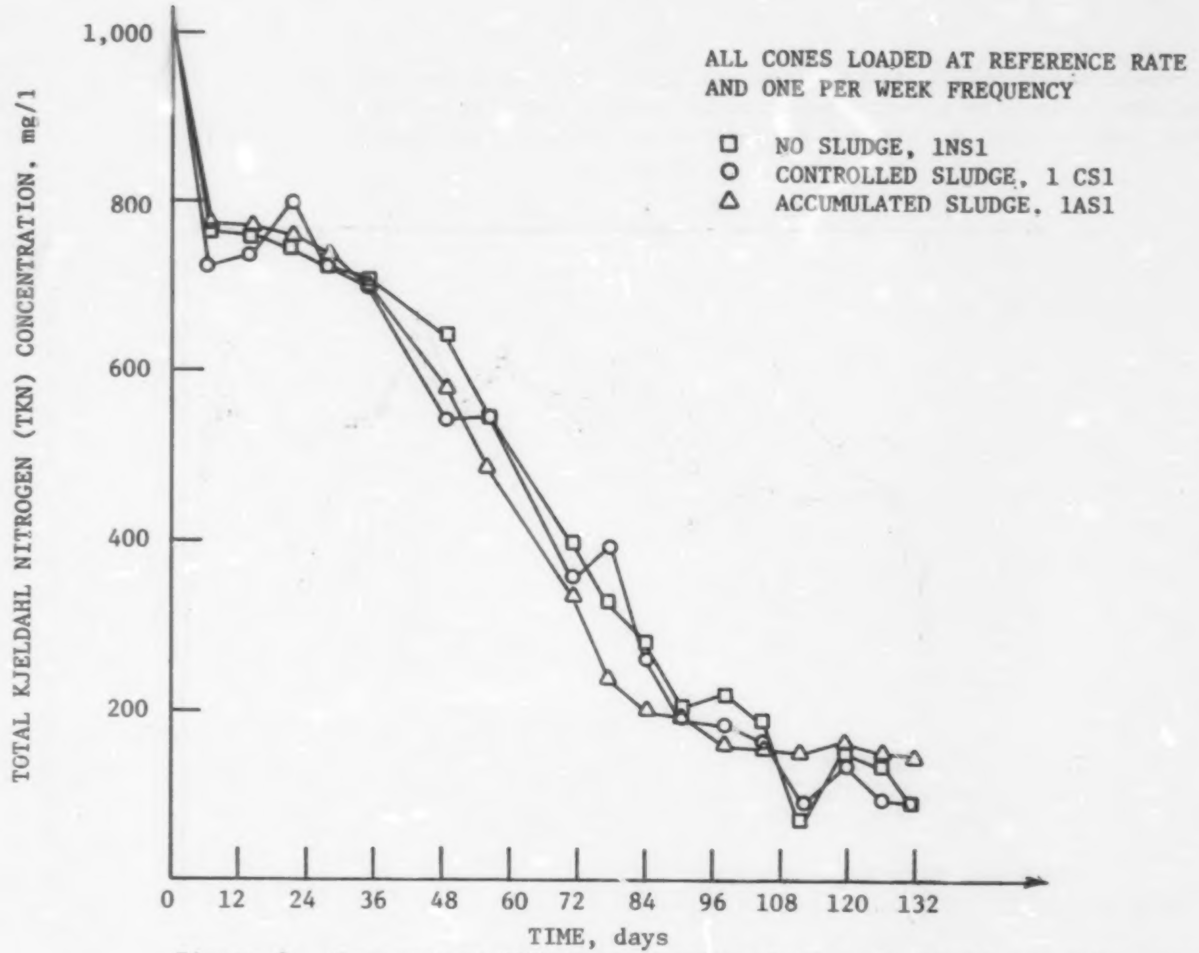


Figure 6. Supernatant TKN concentration changes in Imhoff cones begun with swine waste lagoon supernatant with or without sludge as inoculum and loaded with raw swine waste (first experimental set).

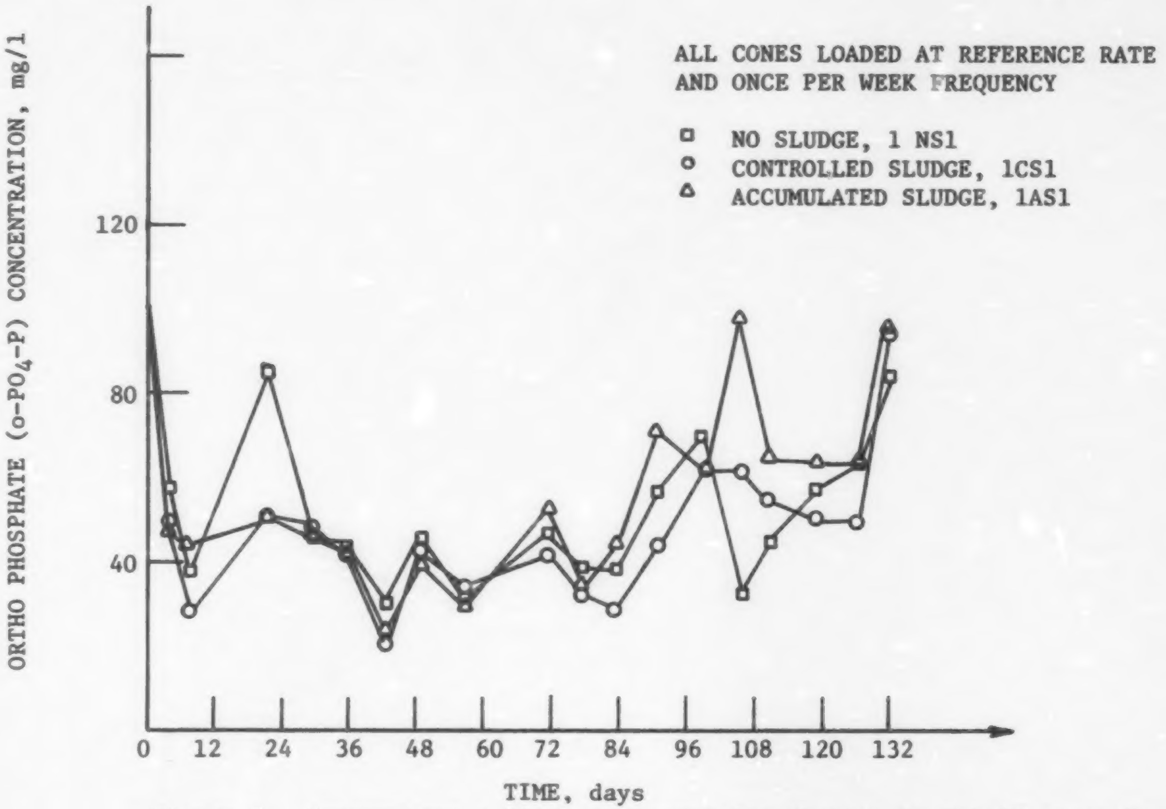


Figure 7. Supernatant o-PO$_4$-P concentration changes in Imhoff cones begun with swine waste lagoon supernatant with or without sludge as inoculum and loaded with raw swine waste (first experimental set).

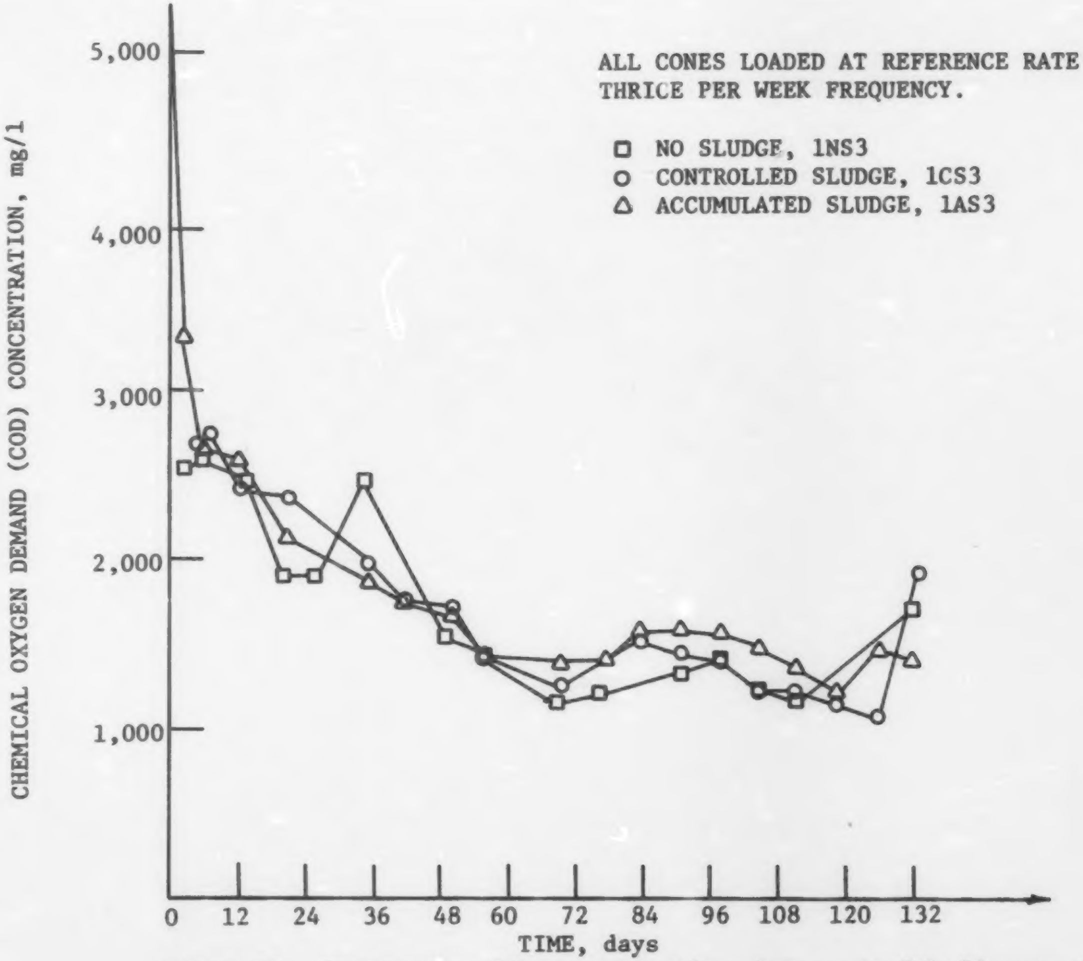


Figure 8. Supernatant COD concentration changes in Imhoff cones begun with swine waste lagoon supernatant with or without sludge as inoculum and loaded with raw swine waste (first experimental set).

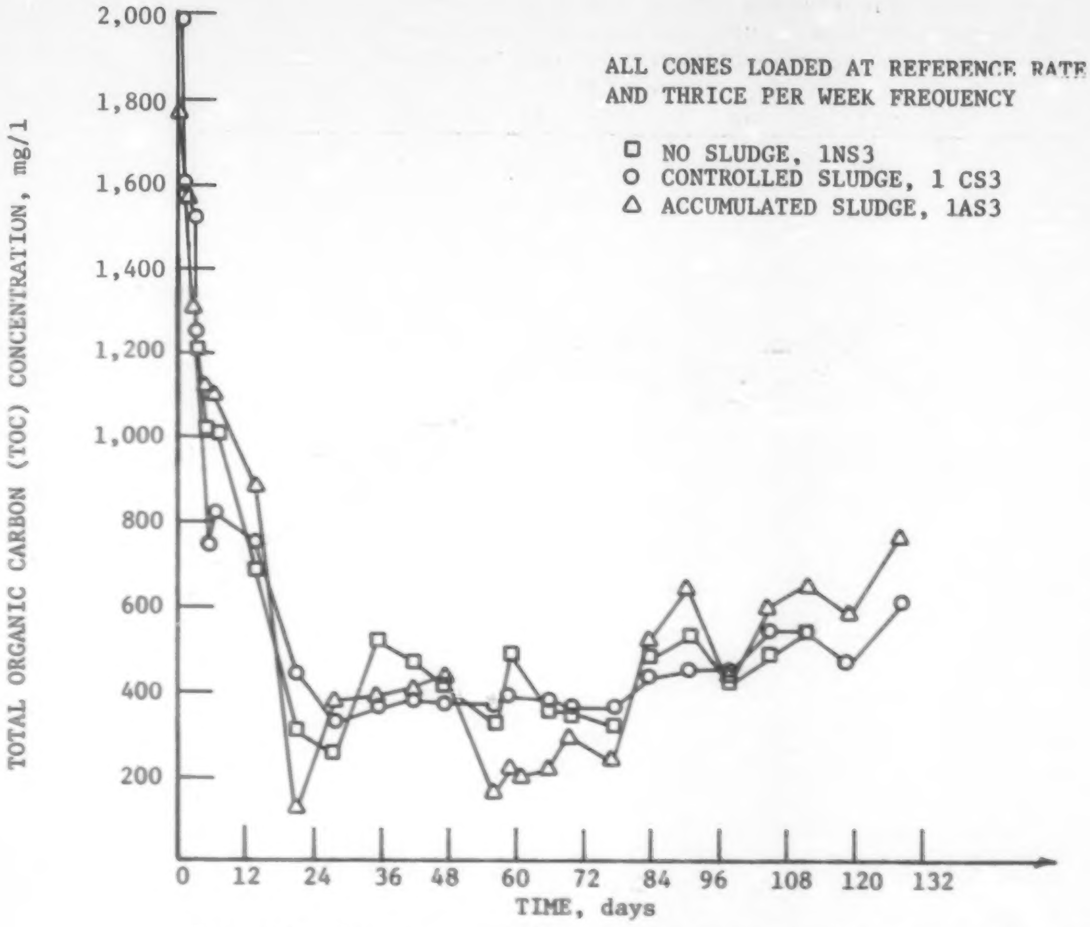


Figure 9. Supernatant TOC concentration changes in Imhoff cones begun with swine waste lagoon supernatant with or without sludge as inoculum and loaded with raw swine waste (first experimental set).

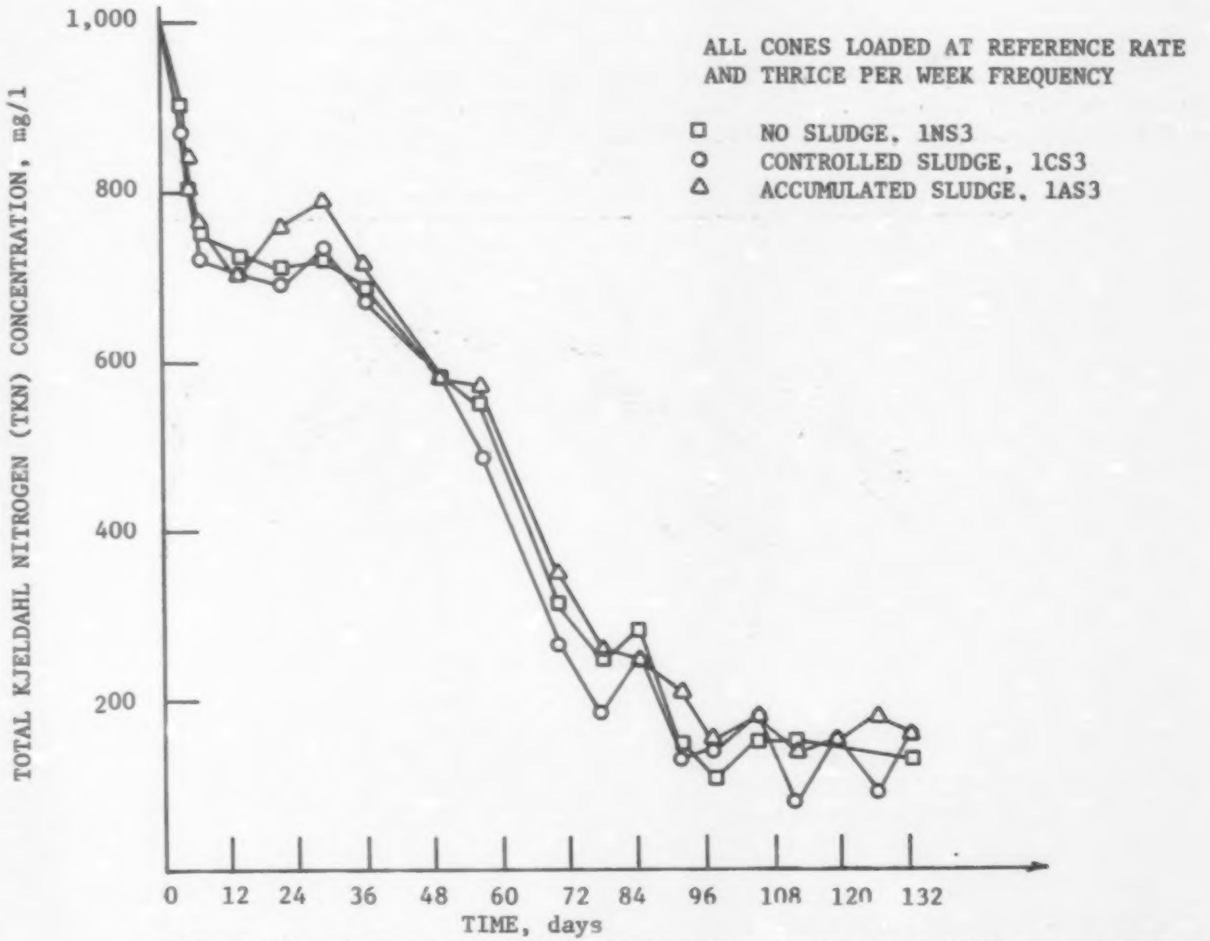


Figure 10. Supernatant TKN concentration changes in Imhoff cones begun with swine waste lagoon superantant with or without sludge as inoculum and loaded with raw swine waste (first experimental set).

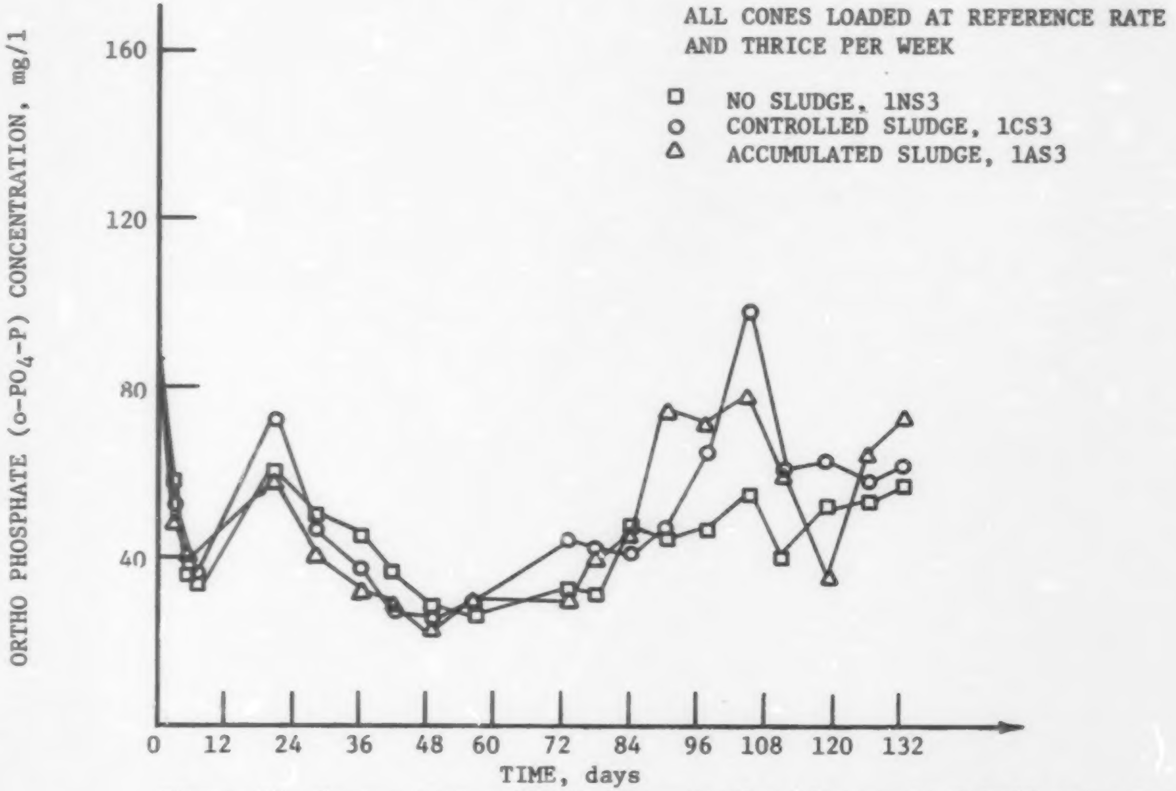


Figure 11. Supernatant o-PO$_4$-P concentration changes in Imhoff cones begun with swine waste lagoon supernatant with or without sludge as inoculum and loaded with raw swine waste (first experimental set).

volumes, concentrations, and other data used in these calculations are listed in Appendix A2. The discussion of these data and overall mass balances are included at the end of the Imhoff Cone Loading Rate and Sludge Management Section.

Table 8. SLUDGE OR SETTLED SOLIDS RECOVERY FOR SEVERAL SLUDGE MANAGEMENT TECHNIQUES FROM IMHOFF CONES RECEIVING SWINE WASTE INPUTS

	Sludge Recovered			
First experiment: operation	Parameter	Amount, mg	As percent of feed	As percent of feed plus precharge
Reference loading rate, no sludge, once per week frequency, 1NS1 (19 weeks)	TKN	360	44	20
	TOC	3,087	79	55
	COD	8,037	58	42
	o-PO_4-P	225	98	66
Reference loading rate, controlled sludge, once per week frequency, 1CS1 (19 weeks)	TKN	283	34	15
	TOC	1,967	50	34
	COD	7,392	54	38
	o-PO_4-P	242	106	71
Reference loading rate, accumulated sludge, once per week frequency, 1AS1 (19 weeks)	TKN	206	25	11
	TOC	1,554	40	27
	COD	4,061	30	21
	o-PO_4-P	229	100	67
Reference loading, rate, no sludge, thrice per week frequency, 1NS3, (19 weeks)	TKN	492	60	27
	TOC	3,087	79	54
	COD	9,368	68	49
	o-PO_4-P	301	131	89
Reference loading rate, controlled sludge, thrice per week frequency 1CS3, (19 weeks)	TKN	304	37	16
	TOC	1,960	50	34
	COD	6,298	46	32
	o-PO_4-P	216	94	64
Reference loading rate accumulated sludge, thrice per week frequency 1AS3, (19 weeks)	TKN	227	28	12
	TOC	1,650	42	29
	COD	4,844	35	25
	o-PO_4-P	220	96	65

Loading Rate and Sludge Management Study-

A second experiment was begun with one-liter Imhoff cones to investigate a much higher raw waste loading rate with the same three sludge management schemes previously used. Two sets of cones were used, both loaded once per week. The first set was similar to the earlier cones in that the reference loading rate was used. These cones were thus 1NS1, 1CS1, and 1AS1. The second set was loaded at four times the reference rate which meant that the cones received 100 mg of raw swine waste (40,000 mg COD/1) per week corresponding to 0.58 m^3 reactor volume per 45-kg hog. Designation for these cones was 4NS1, 4CS1, and 4AS1.

All cones were initiated with one liter of tap water to allow comparison with the previously seeded cones. The tops were covered again to minimize water vapor loss. The sampling procedure was the same as that previously described with the sample volume still being 20 ml to minimize volume loss. The sludge management was the same as the first Imhoff cone experiment.

Supernatant concentrations of COD, TOC, and TKN reached steady condition in ten to twelve weeks, Figures 12-17. At the completion of the experiment, the supernatant and sludge volume and constituent measurements were made and the corresponding sludge recovery results are shown in Table 9, (detailed data in Appendix A2).

Imhoff Cone Reactor Discussion-

In the first cone experiment, there did not appear to be any differences between the supernatant concentration of COD, TOC, TKN and o-PO_4-P in the no sludge, controlled sludge, and accumulated sludge cones. Also, comparison of Figures 5 and 9 indicates that the more frequent loading (3/week) did not result in a different quality supernatant than the once per week loading. Thus, no concentration difference due to sludge management or loading frequency was evidenced for this investigation.

Table 9. SLUDGE OR SETTLED SOLIDS RECOVERY FOR SEVERAL SLUDGE MANAGEMENT TECHNIQUES FROM IMHOFF CONES RECEIVING SWINE WASTE INPUTS

Second experiment: operation	Sludge Recovered		
	Parameter	Amount, mg	As percent of feed
Reference loading rate, no sludge, once per week frequency, 1NS1, (29 weeks)	TKN	549	27
	TOC	2,787	30
	COD	10,332	36
Reference loading rate, controlled sludge, once per week frequency, 1CS1, (29 weeks)	TKN	280	14
	TOC	1,939	21
	COD	5,617	19
Reference loading rate, accumulated sludge, once per week frequency 1AS1, (23 weeks)	TKN	306	18
	TOC	1,538	20
	COD	5,325	22
Four times the reference loading rate, no sludge, once per week frequency, 4NS1, (16 weeks)	TKN	1,573	38
	TOC	9,028	38
	COD	33,742	57
Four times the reference loading rate, controlled sludge, once per week frequency, 4CS1, (16 weeks)	TKN	1,455	35
	TOC	8,126	34
	COD	32,075	54
Four times the reference loading rate, accumulated sludge, once per week frequency, 4AS1, (16 weeks)	TKN	1,288	31
	TOC	5,183	22
	COD	16,923	28

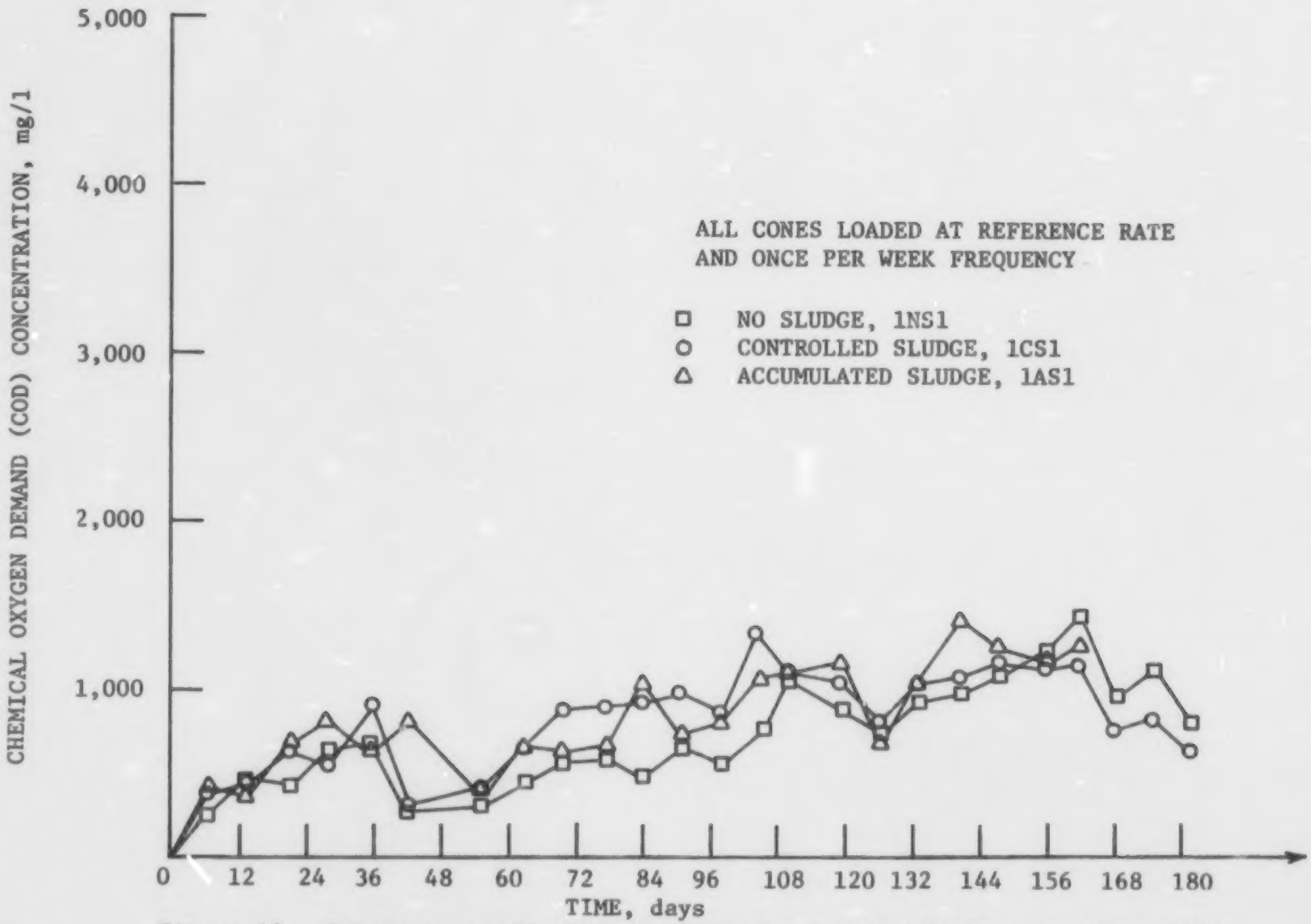


Figure 12. Supernatant COD concentration changes in Imhoff cones begun with tap water (second experimental set) and loaded with raw swine waste.

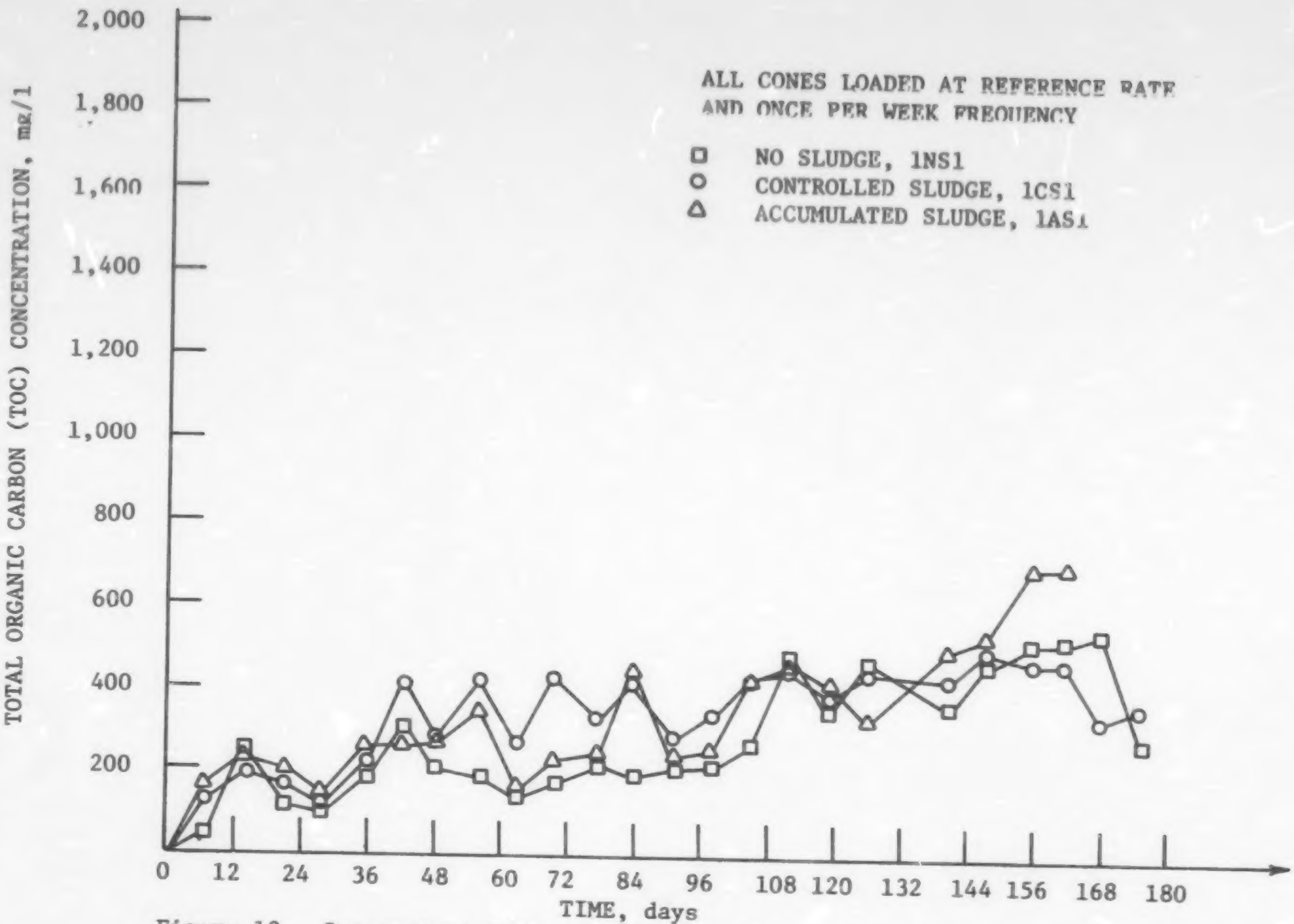


Figure 13. Supernatant TOC concentration changes in Imhoff cones begun with tap water and loaded with raw swine waste (second experimental set).

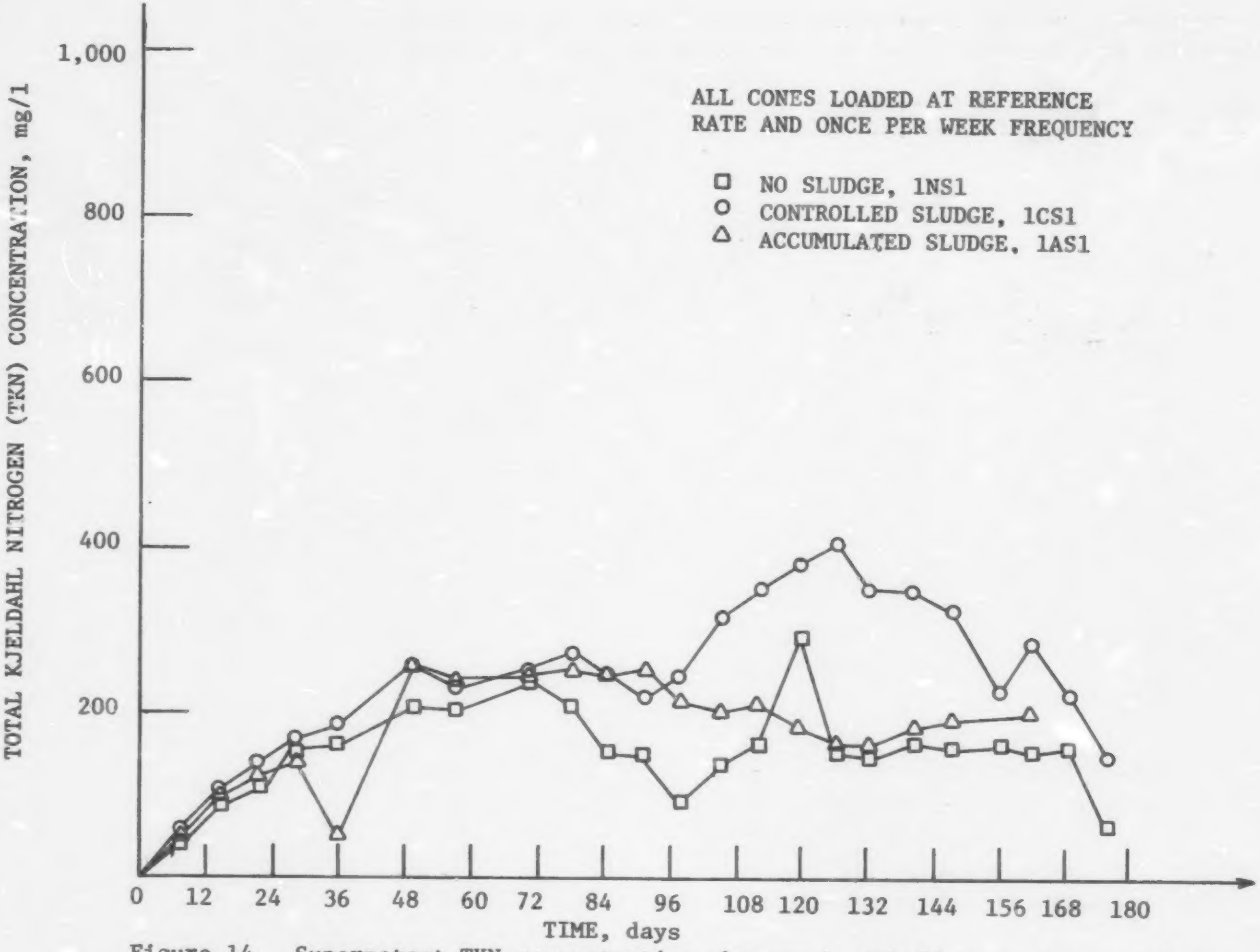


Figure 14. Supernatant TKN concentration changes in Imhoff cones begun with tap water and loaded with raw swine waste (second experimental set).

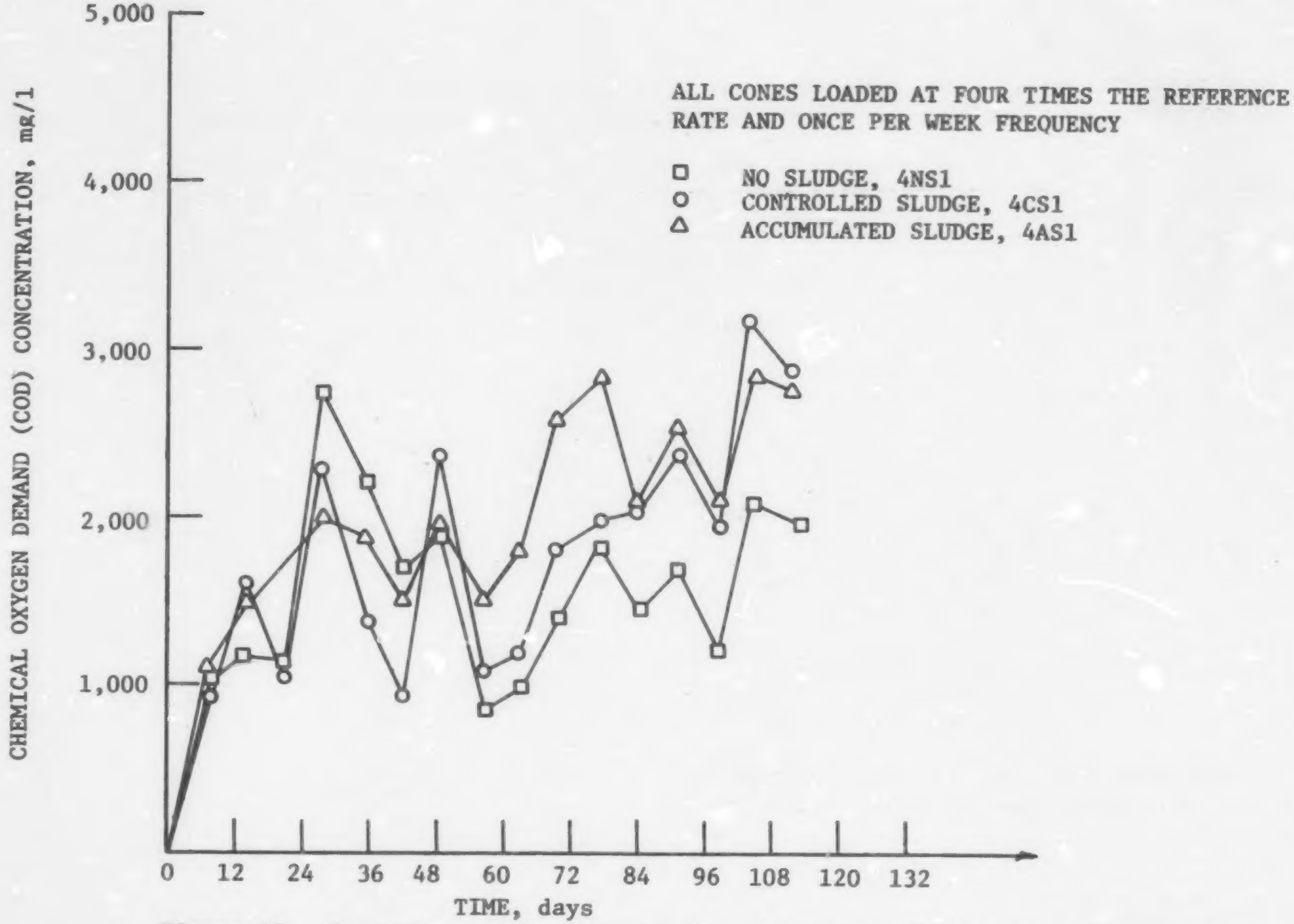


Figure 15. Supernatant COD concentration changes in Imhoff cones begun with tap water and loaded with raw swine wastes (second experimental set).

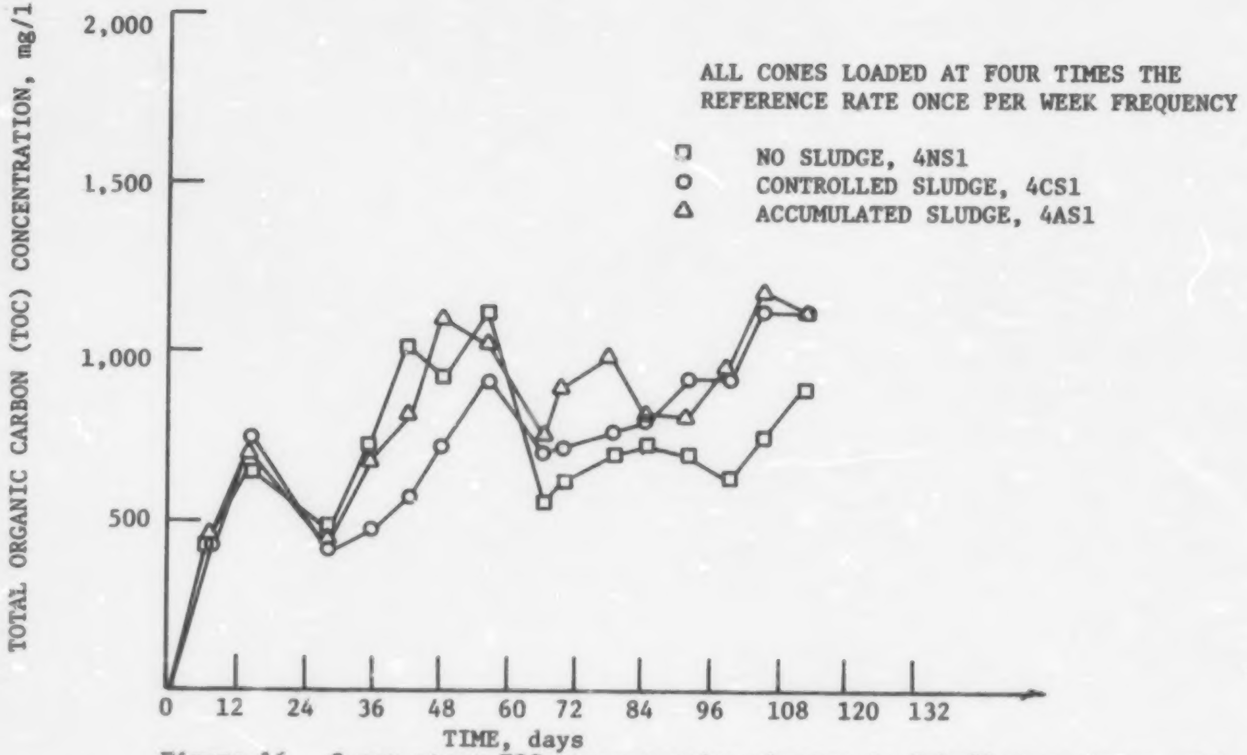


Figure 16. Supernatant TOC concentration changes in Imhoff cones begun with tap water and loaded with raw swine waste (second experimental set).

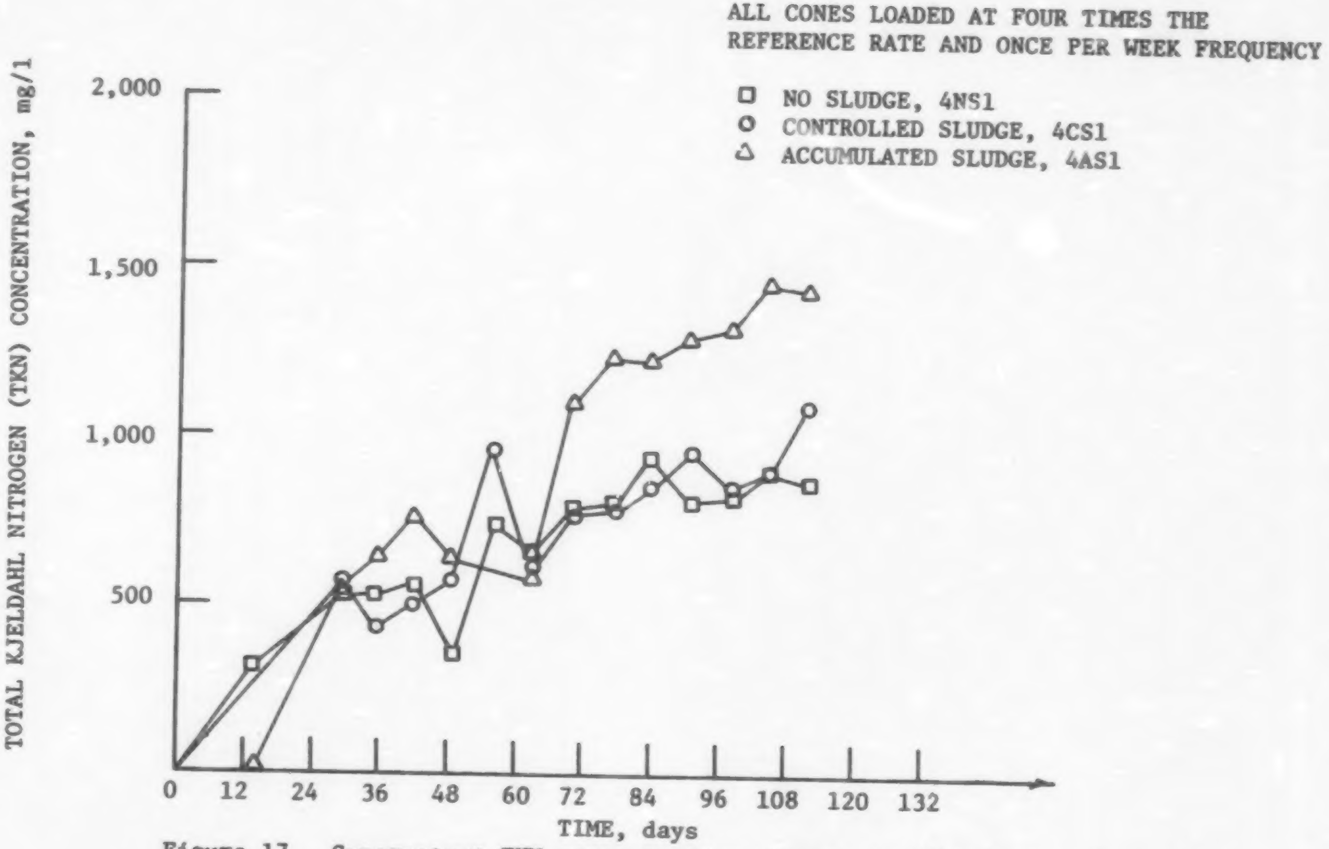


Figure 17. Supernatant TKN concentration changes in Imhoff cones begun with tap water and loaded with raw swine waste (second experimental set).

In the second cone experiment there were occasional periods, for both the reference and the four times reference rate, in which the no-sludge supernatant concentration was lower than the controlled or accumulated sludge cones. There were also periods in which the supernatant concentration for the accumulated sludge cone was higher than the other two sludge management schemes. However in comparing the three waste parameters (COD, TOC, & TKN) over the entire length of both cone experiments the differences in supernatant quality were not significant. That is, results for these tests indicate the presence of a sludge layer and subsequent interfacial transport was a less significant factor in determining supernatant quality than biostabilization and other loss mechanisms ongoing in the supernatant. Thus differences in supernatant quality due to sludge management would not be large enough to warrant an engineered system to control or remove settled solids.

The initial settling of the raw swine waste (40,000 mg COD/1) in an anaerobic supernatant fluid was estimated by the amounts of the various waste parameters recovered from the sludge fraction of 1NS1, 1NS3, and 4NS1. Sludge removal after initial settling or 6 to 8 hours after loading from the no-sludge cones minimized degradative breakdown of the settled solids. A conflicting factor is that the settled material drained from the no sludge cones contained some supernatant because of the difficulty in detecting the exact sludge depth due to solids bridging and other visibility or operational problems. This increased the volume of material drained, but because the supernatant concentration is only about 5 percent of the sludge concentration the inclusion of supernatant did not overly influence the amount of chemical parameters drained from these cones.

An exact percentage estimate of organic or oxygen demanding constituents which settle initially could not be obtained because of the variability between the two cone experiments, Tables 8 and 9. The average percent consituent initially settled for all cone experiments was 55 percent - COD, 56 percent - TOC, and 42 percent - TKN, Table 10. The second experiment was better controlled with less evaporation and more uniform waste input. Thus typical COD and TOC removals with initial settling may be closer to the results of the second experiment (30 percent - 40 percent TOC and 35 percent - 55 percent COD); however, these conclusions are only tentative. In related swine waste experiments by Jett, et al.[80] with .5, 1, and 2 percent total solids mixtures settling was essentially complete after 60 minutes with from 60 percent to 80 percent total solids reduction. Settled solids contain inert materials hence total solids removal would be expected to be higher than COD or TOC removals (10 percent to 80 percent versus 30 percent to 50 percent).

Table 10. INITIAL SETTLING OF SWINE WASTES EVALUATED FROM IMHOFF CONE ANAEROBIC REACTORS (NO SLUDGE)

		Percentage of raw waste input which settled after 6 to 8 hours			
		TKN	TOC	COD	o-PO_4-P
First Experiment	1NS1	44	79	58	98
	1NS3	60	79	68	131
Second Experiment	1NS1	27	30	36	---
	4NS1	38	38	57	---
Average		42	56	55	114

Initial settling values for total Kjeldahl nitrogen were lowest, Table 10, which was expected because about 50 percent - 60 percent of the raw swine waste nitrogen was in the ammonia or ammonium form, Table 6 and thus about 40 percent - 50 percent organic nitrogen. If the settled TKN was all organic it would mean 80+ percent settling for organic nitrogen. It can be assumed that some ammonia was removed by entrapment, precipitation, or another mechanism because organic settling as measured by COD and TOC phase separation of the TKN was only 55 to 65 percent. From the sludge characterization, Appendix B6, sludge nitrogen was found to be 65 percent organic nitrogen and 35 percent ammonia. The raw waste or input was about 40 percent organic nitrogen and 60 percent ammonia.

Data showed that about 90 percent - 100 percent of raw waste total phosphorus settled even though the raw waste was about 70 percent orthophosphorus. Possible mechanisms for this removal were entrapment or precipitation. The latter was more probable since large amounts of settling solids would be required to remove such a high percent o-PO_4-P by physical entrapment. Precipitation has been proposed by Smith et al.[81] and these cone experiments lend further evidence to the importance of the phosphate solubility limit in a swine lagoon system. Various researchers have postulated ammonium magnesium phosphate (NH_3MgPO_4) as the precipitated salt which has a gray flake structure. Problems with pump or pipe occlusion have been attributed to this precipitation especially in areas with high water hardness or magnesium content.

It was very difficult to maintain the sludge at a constant level in the controlled sludge cones due to the resulting opaque conditions. Thus, the solids residence time varied throughout the experiment and it was difficult to draw any quantitative conclusions about percent removals or degradation. In the first set of experiments, the average sludge residence time was five weeks for the controlled sludge cones (CS) as compared with ten weeks for the accumulated sludge cones (AS) and 6-8 hours for the no sludge (NS) cone tests. In the second experiment, average solids residence time for the controlled sludge cones was four weeks versus fifteen weeks and 6-8 hours for the accumulated and no sludge cones, respectively. The settled solids residence times in the controlled sludge cones, although variable, were intermediate to the residence times for the accumulated and no sludge cones. The amount of COD, TOC, and TKN remaining in the controlled sludge cones was also intermediate to the other two sludge schemes. However, the exact decomposition could not be estimated because of residence time differences and other difficulties described above and verified by the erratic data summarized in Appendix A1.

The accumulated sludge cones had an average sludge residence time of 10-15 weeks (one half the total experiment span). Sludge recoveries as a percentage of the raw waste input were 20 percent to 35 percent COD, 20 percent to 40 percent TOC, 20 percent to 30 percent TKN, and 95 percent to 100 percent o-PO_4-P. These percentages were fairly uniform for both sets of cone experiments. The differences between no sludge and accumulated sludge cones were dramatic. About 40 percent to 50 percent of the COD, TOC and TKN which settled initially had been stabilized or liberated and thus was not present in the sludge zone in the accumulated sludge cones. This partially explained the slow rate of sludge accumulation in actual lagoons. As expected, phosphorus compounds were conservative; and the same percentages were present in all three sludge management alternatives.

The microbial activity in the supernatant zone relative to the sludge zone were calculated from the results of the cone experiments. From the initial settling data, the percent of the raw waste entering the supernatant and the sludge layers was calculated. The initial assumption was made that there was no transfer between supernatant and sludge zones. For the COD, the partition was approximately 60 percent to the sludge and 40 percent to the supernatant. The expected concentration of the supernatant portion of the raw waste input (40,000 mg/l) was then:

$$\begin{array}{l}\text{Hypothetical COD}\\ \text{of the supernatant}\\ \text{fraction of raw}\\ \text{swine waste}\end{array} = \frac{(40{,}000\ \text{mg COD/l})(.40)(\text{feed volume})}{(\text{feed volume})(1-\text{fraction of feed volume which is settled solids})} \tag{1}$$

This equation would give the hypothetical supernatant concentration of COD if the raw waste was allowed to settle.

The fraction of the feed volume considered settleable solids varies considerably depending on the measurement technique or the experiment performed. However from the literature the fraction which is settled solids ranged from a maximum of 50 percent to a minimum of 10 percent and thus the hypothetical supernatant input COD would be between 18,000 mg COD/l to 32,000 mg COD/l, equation 1. Comparing this input concentration range with the steady-state supernatant concentration measured in this study, Figures 4 and 8, the percentage of non-settled waste input remaining in the supernatant was 3 percent - 10 percent.

The reduction of sludge COD was estimated by the amount left in the accumulated sludge divided by the amount drained from the no-sludge cones or approximately 50 percent - 60 percent. For the COD, a comparison of the amount remaining in the supernatant phase versus the sludge phase as a percent of the amount entering those phases indicated a much greater level of stabilization in supernatant versus the sludge (3 percent - 10 percent remaining versus 50 percent - 60 percent remaining). This ratio indicated a higher level of microbial activity and hence higher potential for waste stabilization in the supernatant than in the sludge zone. The relative supernatant and sludge levels of removal for TKN, TOC, and COD are given in Table 11. The ratio of percent remaining in sludge to supernatant was large for the carbonaceous parameters, but slightly less for nitrogen. Thus a restriction in the removal of supernatant nitrogen, a volatilization process, was indicated since the sludge removals for carbon and nitrogen compounds were nearly equal, Table 11.

Table 11. RELATIVE SUPERNATANT AND SLUDGE REMOVAL LEVELS FOR IMHOFF CONES WITH ACCUMULATED SLUDGE AND LOADED WITH SWINE WASTE

Parameter	Percent of amount entering sludge which remained	Percent of amount entering supernatant which remained	Ratio of percent remaining in sludge to that of the supernatant
Total Organic Carbon, TOC	55	3 - 10	6 - 18
Chemical Oxygen Demand, COD	52	3 - 10	5 - 17
Total Kjeldahl Nitrogen, TKN	60	7 - 15	4 - 8

Further evidence that there was a partial restriction on nitrogen loss from these loosely covered Imhoff cones was obtained near the end of the second experiment. After steady-state concentration levels of TKN and NH_3-N were achieved the lid was removed and the supernatant concentration monitored, Figure 18. There were slight reductions in the NH_3-N and correspondingly the TKN level indicating increased surface volatilization. However, the final supernatant concentrations were not greatly different from those with the lid present as compared to the input raw waste concentrations. The 2 to 4 cm of freeboard in the cones was probably as restrictive of air flow over the liquid surface as the loosely fitting lids.

The comparison of the no-sludge, controlled sludge, and accumulated sludge cones was designed to clarify the mass transfer exchange across the sludge-supernatant interface. The major removal mechanism for organic carbon or nitrogen compounds is gasification and subsequent volatilization from the supernatant surface. Thus some sludge decomposition products will diffuse into the supernatant phase. The no-sludge cone had an immediate sludge-supernatant separation; hence, relatively no opportunity for sludge decomposition product transfer to the supernatant existed. Therefore a lower supernatant concentration was expected. The comparison of the controlled sludge, representing the upper surface of sludge blanket with the accumulated sludge cones would indicate whether the surface layer or the entire sludge zone has the greatest impact on the supernatant. The controlled and accumulated sludge cone should have interfacial transfer and hence higher supernatant concentrations than the no-sludge cone.

Examination of the sludge recovery data, Tables 8 and 9, provided secondary evidence of the interfacial mass transfer. Constituents reduced in the sludge can be inferred as entering the supernatant directly or as metabolic byproducts. Regardless of parameter (COD, TOC, TKN) the total mass drained from the accumulated sludge (1AS1, 1AS3, 4AS1) and controlled sludge cones was 45 percent - 67 percent and 65 percent - 95 percent of the amount drained from the no-sludge cones (6-8 hours after loading), respectively.

However the supernatant concentration in cones with different sludge management were not significantly different, Figures 4-17. Postulated reasons were that the supernatant contained a high level of microbial activity which with once per week loading was very probably underutilized. Thus these microorganisms effectively used sludge byproducts as well as the raw waste input as substrates masking any differences in interfacial transfer. Another mechanism which would diminish any supernatant differences would be the direct liberation of breakdown products from the sludge to the atmosphere. The bubbles carrying carbon dioxide and methane, which evolve from anaerobic reactors, were evidence of this direct sludge atmosphere loss. Obviously more precise experiments

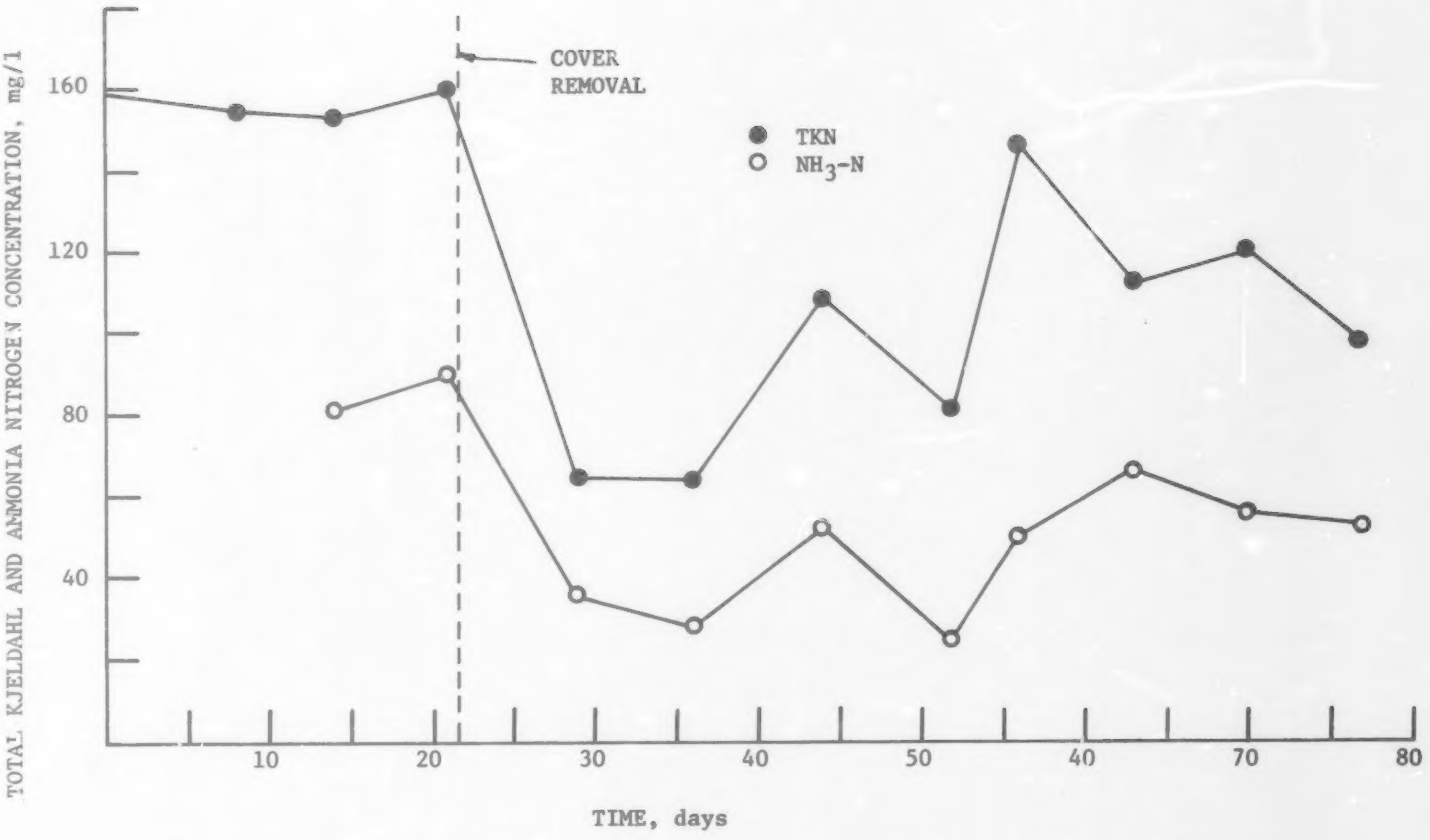


Figure 18. Supernatant TKN and NH_3-N changes associated with removal of the evaporative loss reduction cover from the Imhoff cones.

will be needed to quantify the sludge-supernatant exchange inferred in these experiments.

These data indicating sludge loss of the carbonaceous compounds corroborated the conclusions drawn earlier about the level of supernatant microbial activity. If some or all of the sludge breakdown products entered the supernatant the hypothetical fraction of raw waste COD in the supernatant would be increased, Equation 1. Supernatant concentrations remaining at a steady state would then become a smaller percentage of the total hypothetical COD entering the supernatant. Thus the amount of nutrients remaining in the supernatant would be even smaller in comparison to the sludge than calculated earlier and thus the supernatant biochemical activity even larger.

In an effort to further refine the measurements of swine waste settling and biological activity, total coliform microbial counts were performed immediately after loading on supernatant samples. Typical data over a 5-hour period are shown in Figure 19. Observation of the large population present (1×10^8 to 10^9 total coliform/100 ml) makes the reasons obvious why lagoon supernatant is not suitable for direct stream discharge. Stream standards for total coliform are on the order of 1×10^4 coliform per 100 ml. The time for bacteria population doubling is on the order of .5 to 1 hour; and although the coliform density data were somewhat erratic, an increase in total coliform can be seen over the initial five-hour time span. Qualitative conclusions were that the microbial population maintained a steady viability throughout the latter part of the week after the initial organic material was metabolized. Possibly the mass transfer from the sludge helped maintain this large viable population. Then after loading, a rapid response occurred resulting in organic stabilization. Thus the full microbial capacity of the system was probably not utilized with once per week loading.

Occasionally when animal producers install anaerobic lagoons, designers have recommended sludge seeding for faster start-up response. This is also a common practice for digestors at municipal waste treatments. However comparison of Figures 4 and 5 with Figures 12 and 13 showed that for the reference loading rate at a once per week frequency, the time to achieve steady state supernatant concentration for these two sets of cones was 12-15 weeks. Yet one set of cones had seeded supernatant and sludge while the other was begun with tap water. This accentuates the fact that animal waste is quite concentrated and contains all the microflora needed for adequate anaerobic stabilization. These data do not, however, contradict suggestions to provide waste dilution during lagoon start-up.

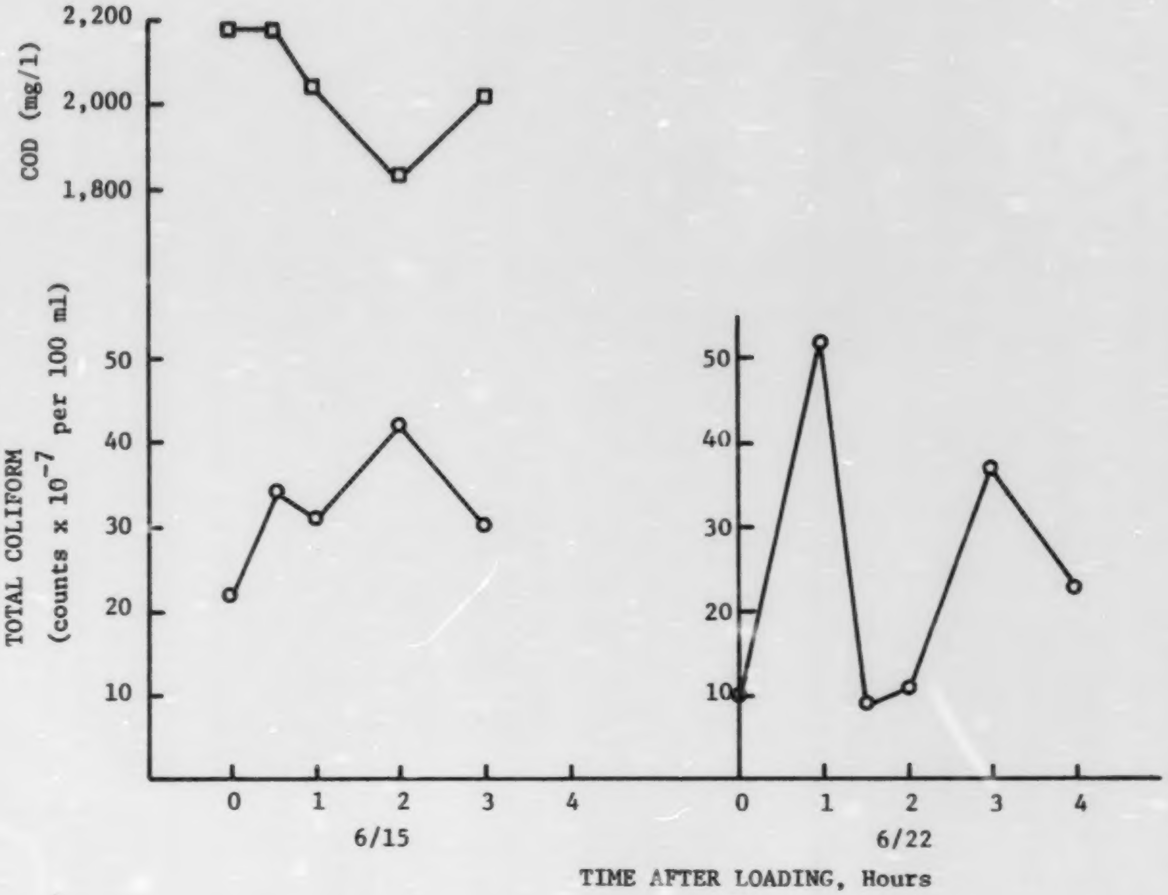


Figure 19. Microbial population and supernatant COD concentration changes immediately after loading laboratory reactors.

Potential existed for significant concentration gradients with depth in both small-scale and field-scale units and thus a single sample could have inadequately portrayed average supernatant concentrations. The concentration of four waste parameters at the top, middle, and bottom of the reactor fluid are listed in Table 12. Results for the bottom sample were somewhat higher due to hindered settling and side wall effects at the cone apex. In general, there appeared to be no large gradients especially in the bulk of the supernatant (the middle and top). This uniformity of supernatant except for top algal or sludge mats was found in many laboratory reactors and field units and is discussed in a later section.

Table 12. SAMPLES TAKEN AT SEVERAL DEPTHS IN IMHOFF CONE AND 14-1 LABORATORY REACTORS LOADED WITH SWINE WASTES

Reactor	Height above bottom, cm	Parameter concentration, mg/l			
		TOC	COD	TKN	o-PO_4-P
1NS1	42	380	820	97	31
	26	315	930	92	57
	1.2	485	1,383	91	63
1NS3	42	330	805	87	56
	26	345	883	83	6[illegible]
	1.2	525	915	114	71
1NS1	42	400	--	112	54
	33	400	--	125	56
	26	450	--	146	56
	19	575	--	174	57
	14	575	--	145	60
14 1 - 3 loads per week	25	--	1,635	380	
	17	--	1,600	290	
	12	--	1,770	360	
	7	--	1,920	360	

For each cone the overall mass balance was calculated by comparing the inputs versus the sum of outflow plus accumulation for four waste constituents, COD, TOC, o-PO_4-P, and TKN. Detailed data for these four components are listed in Appendices A1 and A2. The input included the raw waste feed plus initial seeding. Output was the sum of all the samples taken plus any drained sludge. Accumulation included the remaining supernatant, sludge and any material adhering to the cone walls.

The difference between total input and accumulation plus outflow was termed the amount unaccounted for; which expressed as a percent of the total input, is shown in Table 13. This material was lost from the total system as either volatilization or conversion to gaseous end products. For the COD and TOC this loss was primarily as carbon dioxide and methane evolution while for TKN it would be ammonia volatilization. The total lost from the accumulated sludge units loaded at the reference rate was recorded to be 55 percent - 65 percent for COD, 40 percent - 70 percent for TOC, and 50 percent - 65 percent for TKN. This loss was the same for the once-per-week and three-per-week loading frequencies. The cones loaded at four times the reference rate (4AS1) has about the same COD and TOC losses but a much lower TKN loss. Thus the sludge microbial decomposition of organics was approximately the same at these two very different loading rates and frequencies.

Table 13. OVERALL MASS BALANCE RESULTS FOR ANAEROBIC TREATMENT OF SWINE WASTES - IMHOFF CONE REACTORS WITH VARIOUS SLUDGE MANAGEMENTS

	Percent of cone input which was not recovered as output or accumulation in cone			
	TKN	TOC	COD	$o\text{-}PO_4\text{-}P$
First Experiment				
1NS1	58	20	43	0
1NS3	47	31	38	0
1CS1	63	39	42	0
1CS3	53	38	47	0
1AS1	63	42	57	0
1AS3	56	44	55	0
Second Experiment				
1NS1	66	64	60	-
4NS1	35	55	36	-
1CS1	68	55	64	-
4CS1	28	58	38	-
1AS1	50	62	61	-
4AS1	22	71	64	-

14-1 Reactor Experiments

An assumption, based on the Imhoff cone studies, was that the anaerobic microbes were underutilized at the once-per-week input of raw waste. A series of open-top cylindrical reactors with a tap water volume of 14 l were initiated to evaluate biological response to different nutrient inputs, Figure 20. The reactors were sampled with a wide-tip pipette at mid-depth and then tap water was added to offset evaporative and sampling losses.

Frequency of Loading Studies-

The raw swine waste loading rate in terms of grams of COD per week, was held constant, but the frequency varied. The raw waste concentration was also held constant at 40,000 mg COD/l so that the volume input per week was the same. For example, a unit loaded twice a week received one half the weekly charge at each loading event. The range of loading frequencies employed was once per two weeks, one per week, two per week, and three per week. Because of a calculation-related error, these units were actually loaded at 1.2 times the reference loading or 1.1 kg COD/week/m^3 of reactor, which was thus considered as a nominal reference loading rate. During the initial 26 weeks the raw waste input was lower than 40,000 mg COD/l; therefore, no feed control was exercised until after the 26th week when the raw waste was maintained at about 40,000 mg COD/l.

The weekly concentrations of o-PO_4-P, COD, TOC, and TKN for these four reactors are presented in Figures 21-24. The cyclic behavior of these units was a manifestation of feed strength variations. The supernatant concentration showed no long-term, significant dependence on loading frequency for the range used. The concentration levels of the various units relative to each other changed many times both during start-up and the steady operational periods. The final concentrations of COD, TOC, TKN and o-PO_4-P for all loading frequencies evaluated were about 1,300, 500, 400, and 25 mg/l, respectively. Because of the 20 percent

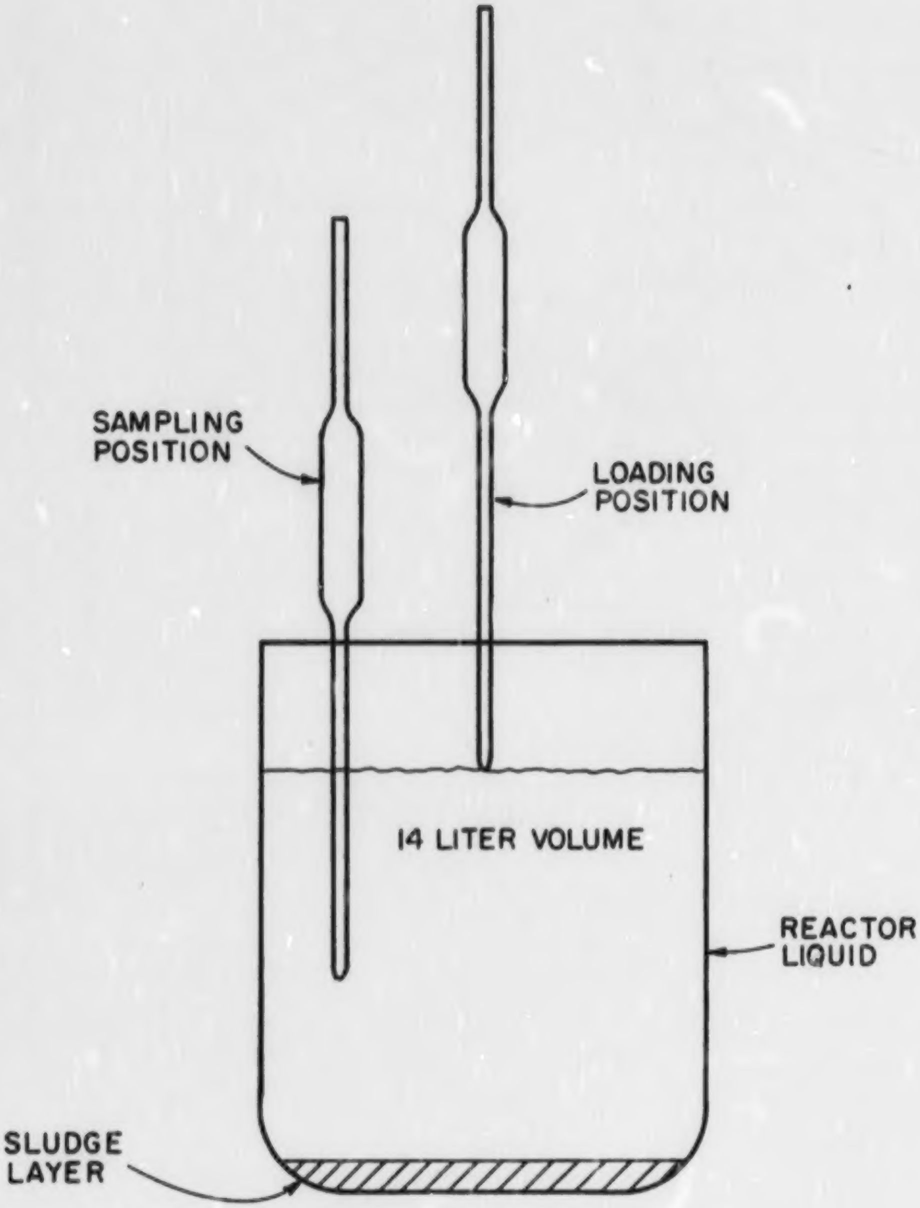

SAMPLING POSITION
LOADING POSITION
14 LITER VOLUME
REACTOR LIQUID
SLUDGE LAYER
Scale 1cm = 4cm

Figure 20. Schematic of 14-l laboratory reactor loaded with swine wastes.

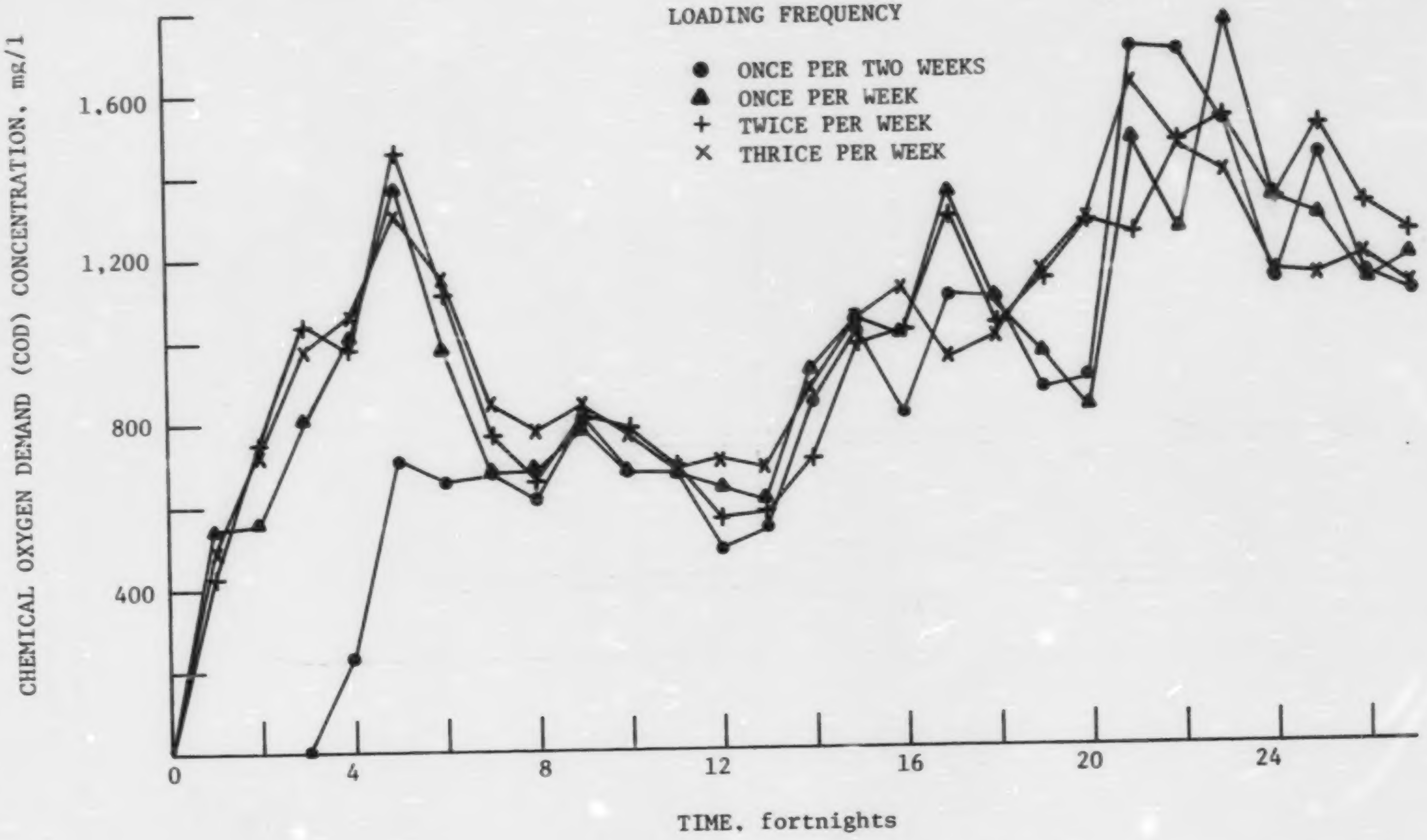


Figure 21. Supernatant COD concentration changes in 14-1 laboratory reactors loaded with swine waste at various frequencies.

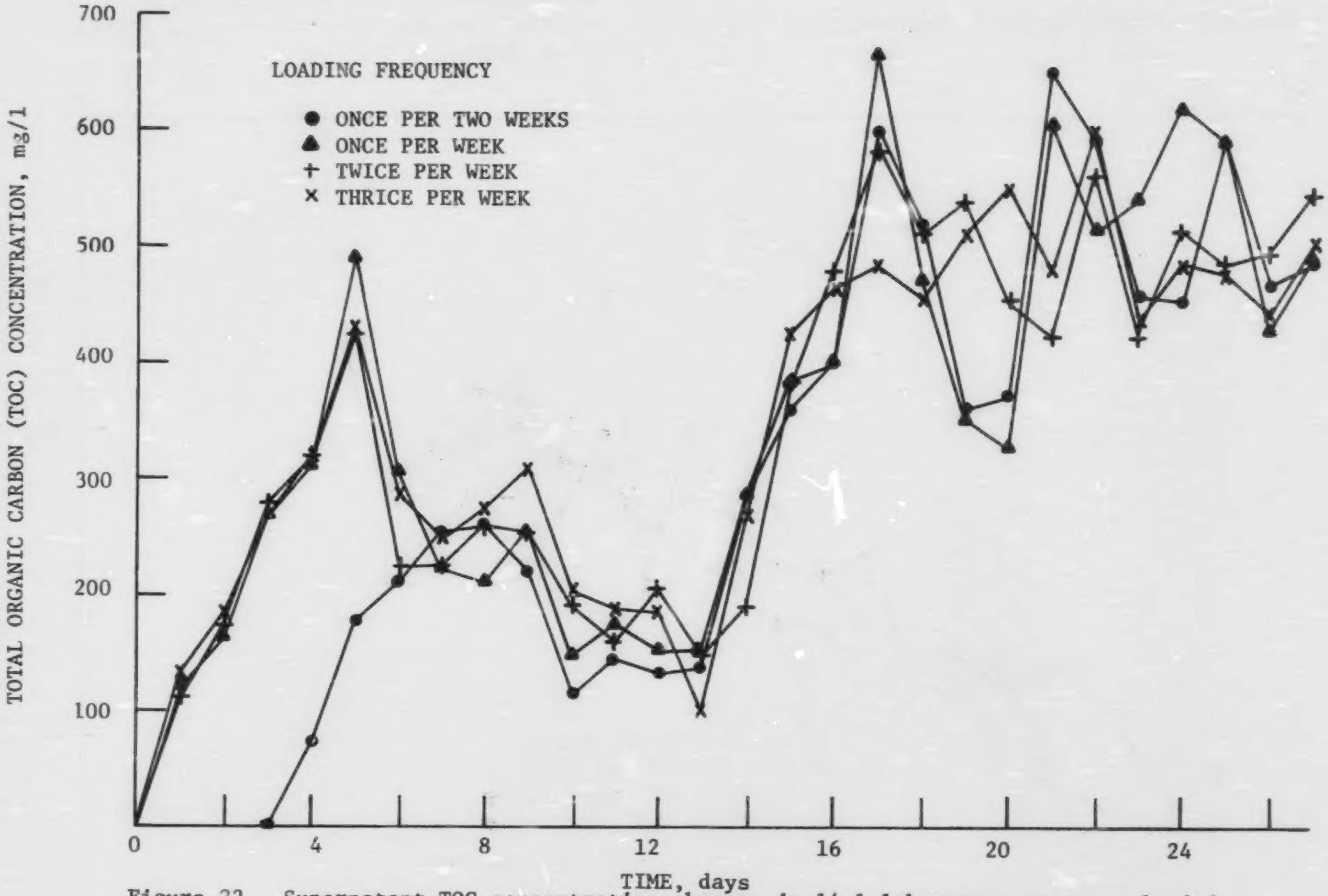


Figure 22. Supernatant TOC concentration changes in 14-l laboratory reactors loaded with swine waste at various frequencies.

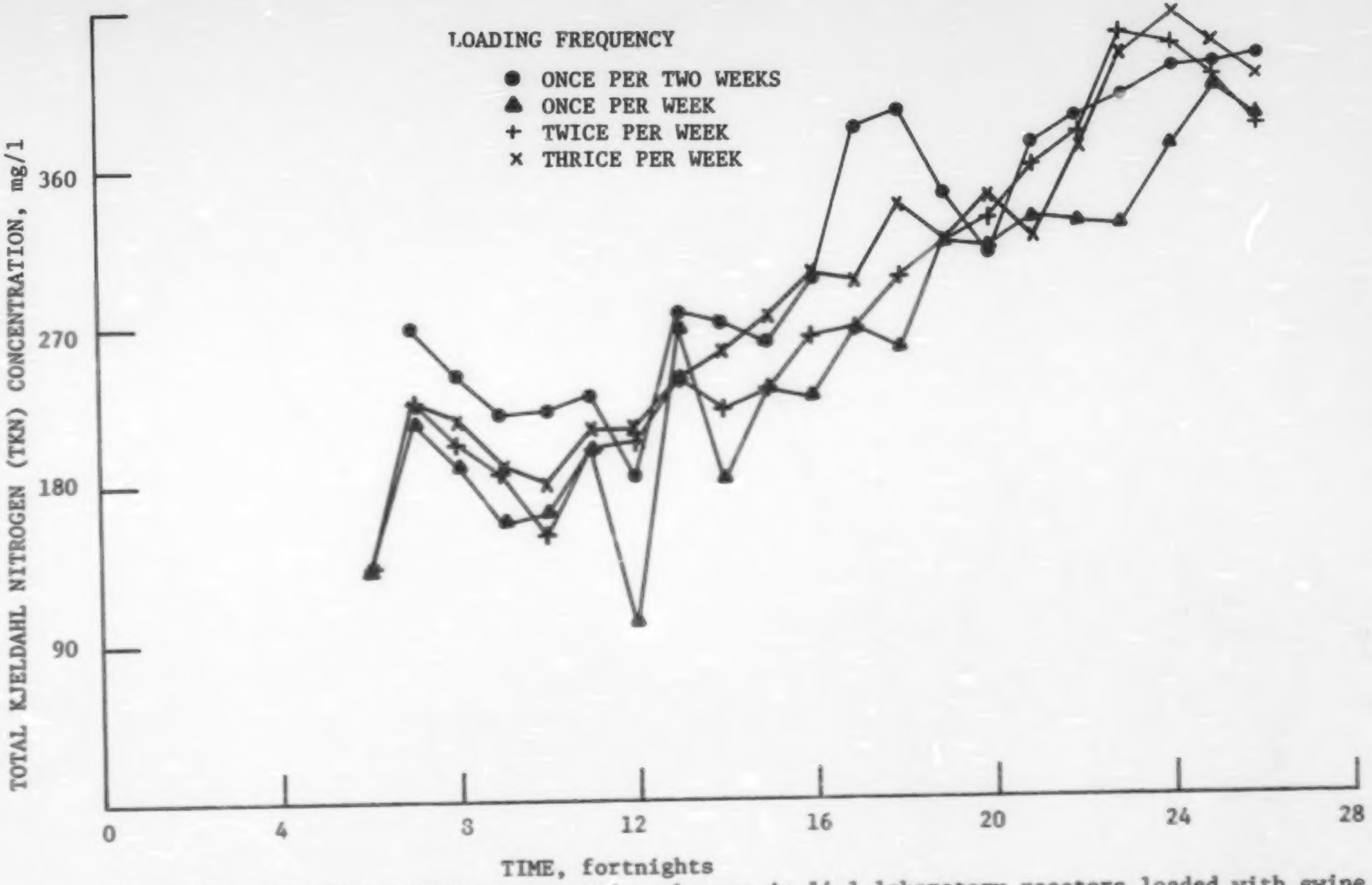


Figure 23. Supernatant TKN concentration changes in 14-1 laboratory reactors loaded with swine waste at various frequencies.

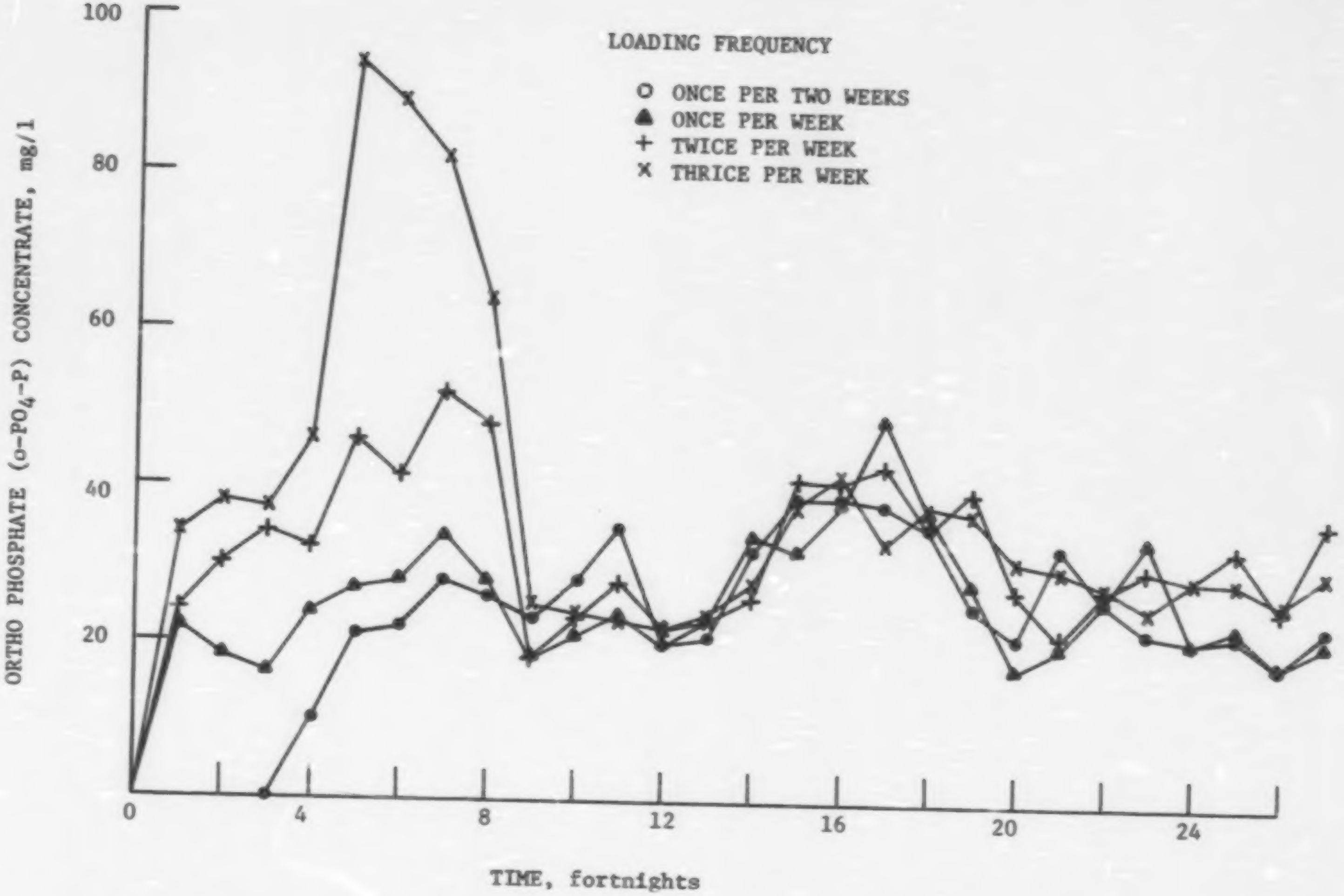


Figure 24. Supernatant o-PO$_4$-P concentration changes in 14-1 laboratory reactors loaded with swine waste at various frequencies.

higher reactor loading rate, the levels of oxygen demand and organic carbon were 10-20 percent higher than cones loaded at comparable rates thus showing the effluent concentration dependence on loading rate. However, the TKN level in the cones was only about 40 percent of the TKN steady-state concentration of 400 mg/l for these 14-l reactors. The final orthophosphate ($o-PO_4-P$) level of these 14-l reactors was the same as for comparable cones, 30-40 mg/l.

After 56 weeks of operation, these four 14-l reactors were stopped and the volume and concentration of both the supernatant and the sludge determined. The amount of COD, TOC, TKN, and $o-PO_4-P$ remaining in the sludge as a percent of the raw waste input are shown in Table 14 and Appendix A3. The 20 percent to 30 percent COD and 20-25 percent TOC remaining compared favorably with the accumulated sludge cone data, Tables 8 and 9. The TKN remaining was about 10 percent less than from similarly loaded Imhoff cones. The 14-l reactors were operated for 56 weeks as compared to 23 weeks for the second cone experiment and 19 weeks for the first cone experiment. Because the percentages of the feed which remained in the sludge was nearly the same over these three experiment durations, there appears to be a steady-state decay level for accumulated bottom sludge. The corresponding percentage of swine waste input COD, TOC and TKN which remained in the sludge for the Imhoff cones and 14-l reactors was 20 percent to 35 percent and 10 percent to 30 percent, respectively.

Table 14. AMOUNT OF WASTE PARAMETERS REMAINING IN SLUDGE ZONE OF ANAEROBIC 14-LITER LABORATORY REACTORS LOADED AT DIFFERENT FREQUENCIES

Loading rate - 1.15 kg COD/week/m^3	Amount remaining in sludge as a percent of the feed		
Loading frequency	TOC	COD	TKN
One time per two weeks	25	29	12
One time per week	21	27	15
Twice per week	25	30	13
Three times per week	21	21	13

The sludge depth in these 14-l reactors was about 2.8 cm when the experiment was completed. In addition to sludge determinations, the bottom 6.4 cm of sludge and liquid was sampled and the corresponding analysis then included the sludge, interfacial region, and bottom supernatant. The comparison of the bottom 6.4 cm with the sludge zone (2.8 cm), Table 15, indicated that the supernatant added very little to the sludge portion. This observation further strengthens earlier estimates that sludge material drained from the Imhoff cones while larger in volume than the actual sludge was close to the correct sludge amount of the various pollutional parameters.

Table 15. COMPARISON OF THE AMOUNTS OF VARIOUS POLLUTIONAL PARAMETERS IN THE SLUDGE ZONE (BOTTOM 2.8 cm) AND THE SLUDGE PLUS LOWER SUPERNATANT ZONE (BOTTOM 6.4 cm)

Reactor	Sludge zone			Sludge plus lower supernatant zone		
	Parameter amount, g			Parameter amount, g		
	COD	TOC	TKN	COD	TOC	TKN
14-1 laboratory reactor 1 load per 2 weeks	249	72	7.3	252	73	8.2
14-1 laboratory reactor 1 load per week	229	61	8.8	232	62	9.5
14-1 laboratory reactor 2 loads per week	256	58	7.8	259	72	8.4
14-1 laboratory reactor 3 loads per week	176	60	7.5	176	61	8.3

The accumulated sludge volumes from the cone and cylindrical reactor experiments expressed as milliliters per week of experiment are given in Table 16. This volume as a percent of the raw waste was about 10 percent - 25 percent as also shown in Table 16. At the reference loading rate, about 2.3 m^3 or 2250 1 per 45-kg hog were provided in the lagoon. The raw waste strength used in this study corresponded to a waste output of 7.5 1/d/45-kg hog. Multiplying the percent of the feed which became sludge times 7.5 1/day gave a sludge build up of .75 to 1.9 1/d/45-kg hog (10 percent - 25 percent accumulation). The available lagoon volume per 45-kg hog divided by this laboratory reactor buildup rate indicated that from 1,000 - 3,000 days would be needed to fill the lagoon with sludge (2.7 - 8.2 years). Experience has indicated that a much slower buildup occurs under field conditions. Thus caution should be exercised in transferring sludge accumulation data to actual field lagoons. Factors such as compaction under greater liquid head, soil incorporation, and long-term, mixed culture, biochemical stabilization could reduce the field lagoon sludge buildup below that measured in the lab.

Table 16. SLUDGE ACCUMULATION FOR SWINE WASTE INPUT TO ANAEROBIC LABORATORY REACTORS

Reactor	Sludge accumulation, ml/week	Total sludge volume as a percentage of input volume
First Imhoff Cone experiment		
1AS1	6.5	26
1AS3	6.5	26
Second Imhoff Cone experiment		
1AS1	6.4	26
4AS1	16	16
14-1 reactors		
Once per two weeks	45	11
Once per week	41	10
Twice per week	41	10
Thrice per week	39	9

The overall mass balance for COD, TOC, TKN and o-PO_4-P calculated as described earlier with the Imhoff cones are given in Table 17 and Appendix A1 and Appendix A2. The amount of COD, TOC, and TKN lost or not recovered from the 14-1 reactors was greater than that determined for the Imhoff cone experiments and no agreement between the cones and reactors is discernible concerning the amount of o-PO_4-P lost. At this time no reason, except the possible contribution of analytical error or reactor configuration differences can be postulated for these differences, especially for phosphorus.

Table 17. OVERALL MASS BALANCE FOR 14 1 ANAEROBIC LABORATORY REACTORS LOADED WITH RAW SWINE WASTE AT VARIOUS FREQUENCIES

Loading Rate: 1.1 kg COD/week per m^3 of reactor volume	Percent of reactor input which was not recovered as output or accumulation			
Loading Frequency	Parameter			
	TKN	TOC	COD	$o\text{-}PO_4\text{-}P$
Once per two weeks	77	71	67	71
Once per week	76	74	72	56
Twice per week	77	71	67	71
Thrice per week	76	74	76	70

To put the loading frequencies of these four units in perspective, the once per two weeks was not infrequent enough to present a shock load to the reactor. Shock loads are characteristic of manure pit management in which the lagoon receives a large charge two or three times per year. Such shock inputs can cause imbalance or overloading which can lead to lagoon failure.[29] Such infrequent loadings were not investigated in this study.

The most frequent loading would be continuous input; hence another comparative study was undertaken to expand the frequency studies. Two reactors (14-1, open top) were established with tap water and provisions for quasi-continuous loading. The loading rates were a) four times the nominal reference load or 4.8 times the reference rate and b) the nominal loading rate. The raw waste input was refrigerated and inputs were once per 4 hours at 10 ml/pumping and once per hour at 10 ml/pumping for the 1.2 and 4.8 times units, respectively. These rates corresponded to 1.1 and 4.4 kg COD/day/m^3 of volume. Two other identical reactors were run at these same loading rates, but with a once per week loading frequency. The supernatant values for these reactors are plotted for the duration of the experiment in Figures 25-30.

The heavier loaded reactors evidenced no significant difference in supernatant quality (COD, TOC, TKN, and $o\text{-}PO_4\text{-}P$) between quasi-continuous and

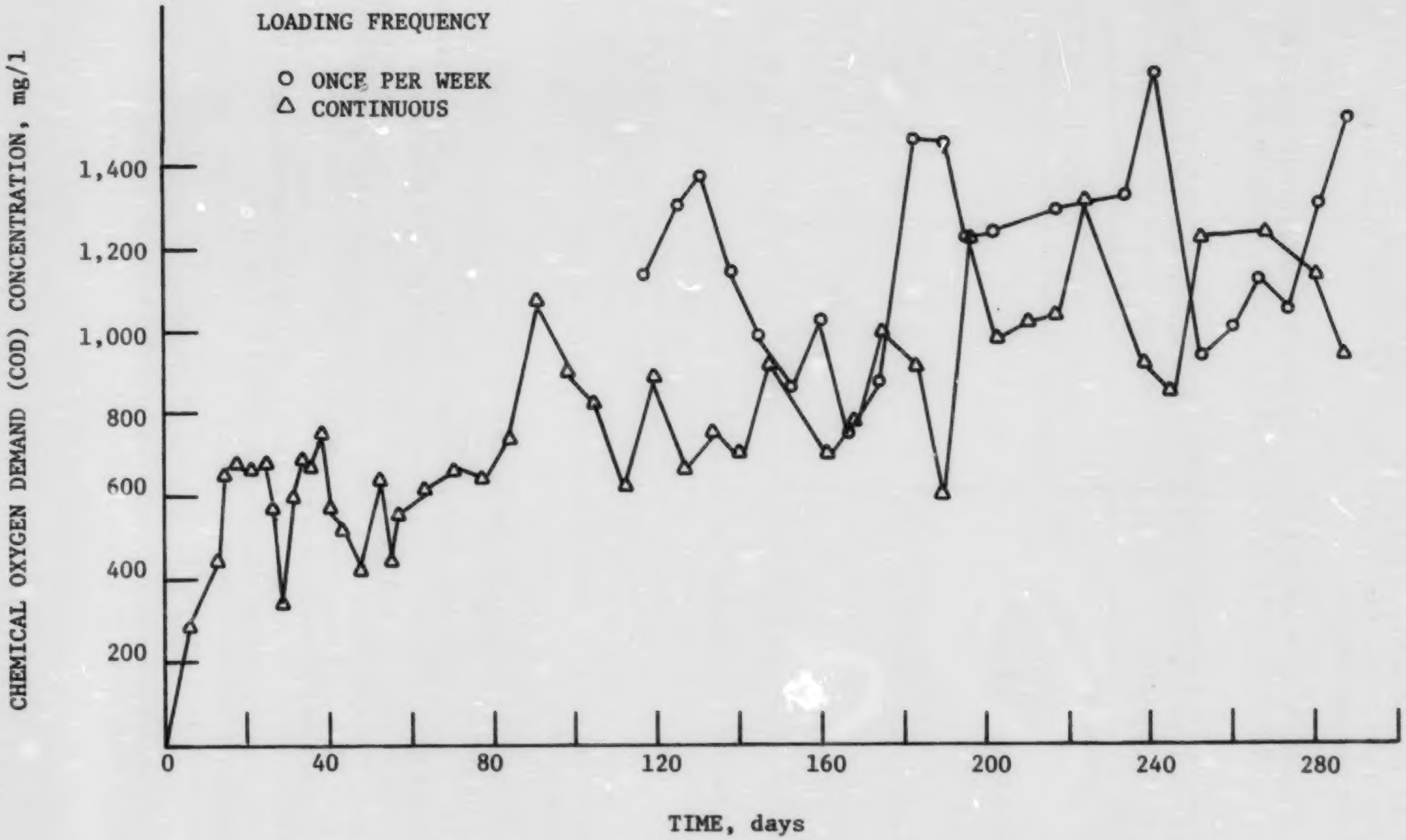


Figure 25. Supernatant COD concentration changes in laboratory 14-1 reactors with the nominal reference loading rate of swine waste on a continuous or batch basis.

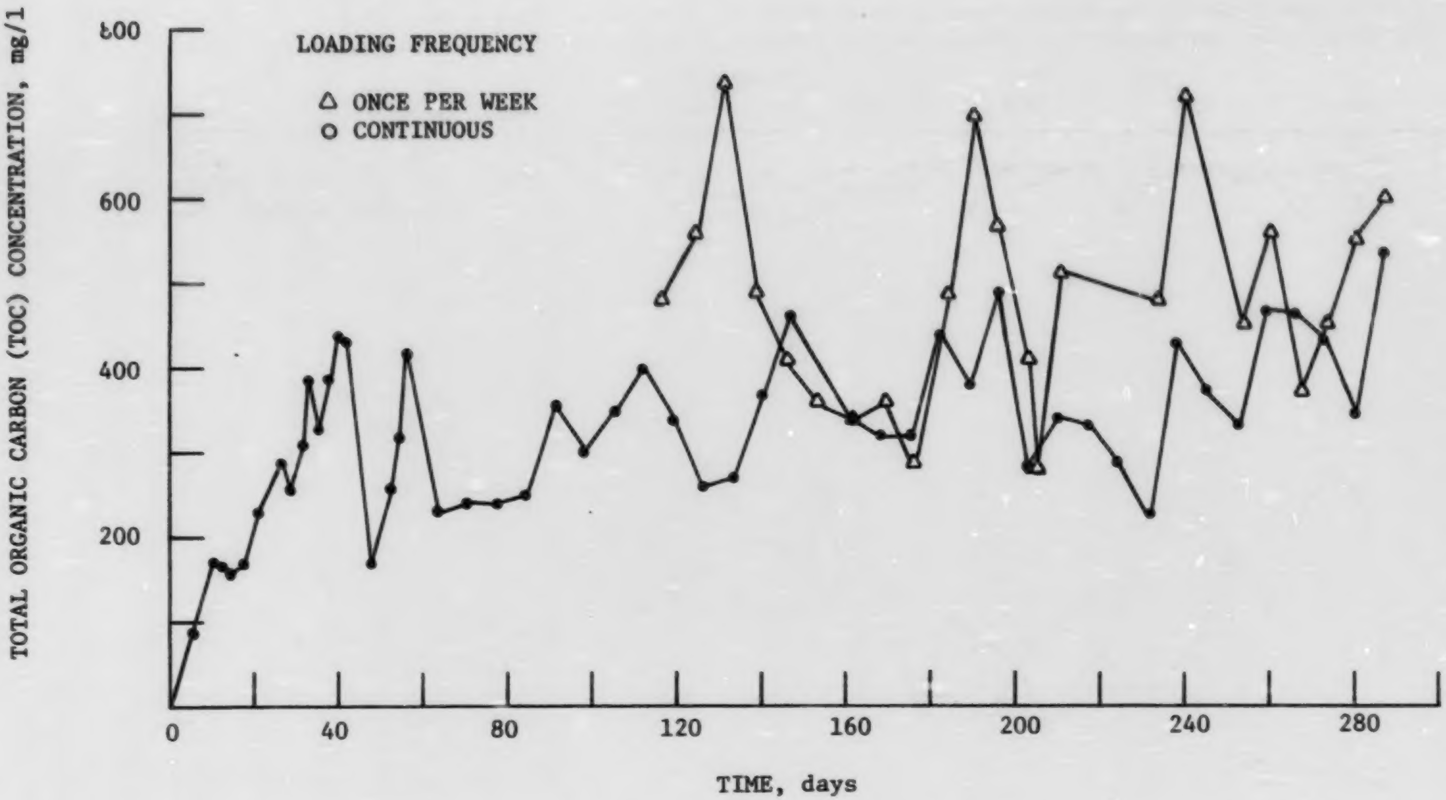


Figure 26. Supernatant TOC concentration changes in laboratory 14-1 reactors with the nominal reference loading rate of swine waste on a continuous or batch basis.

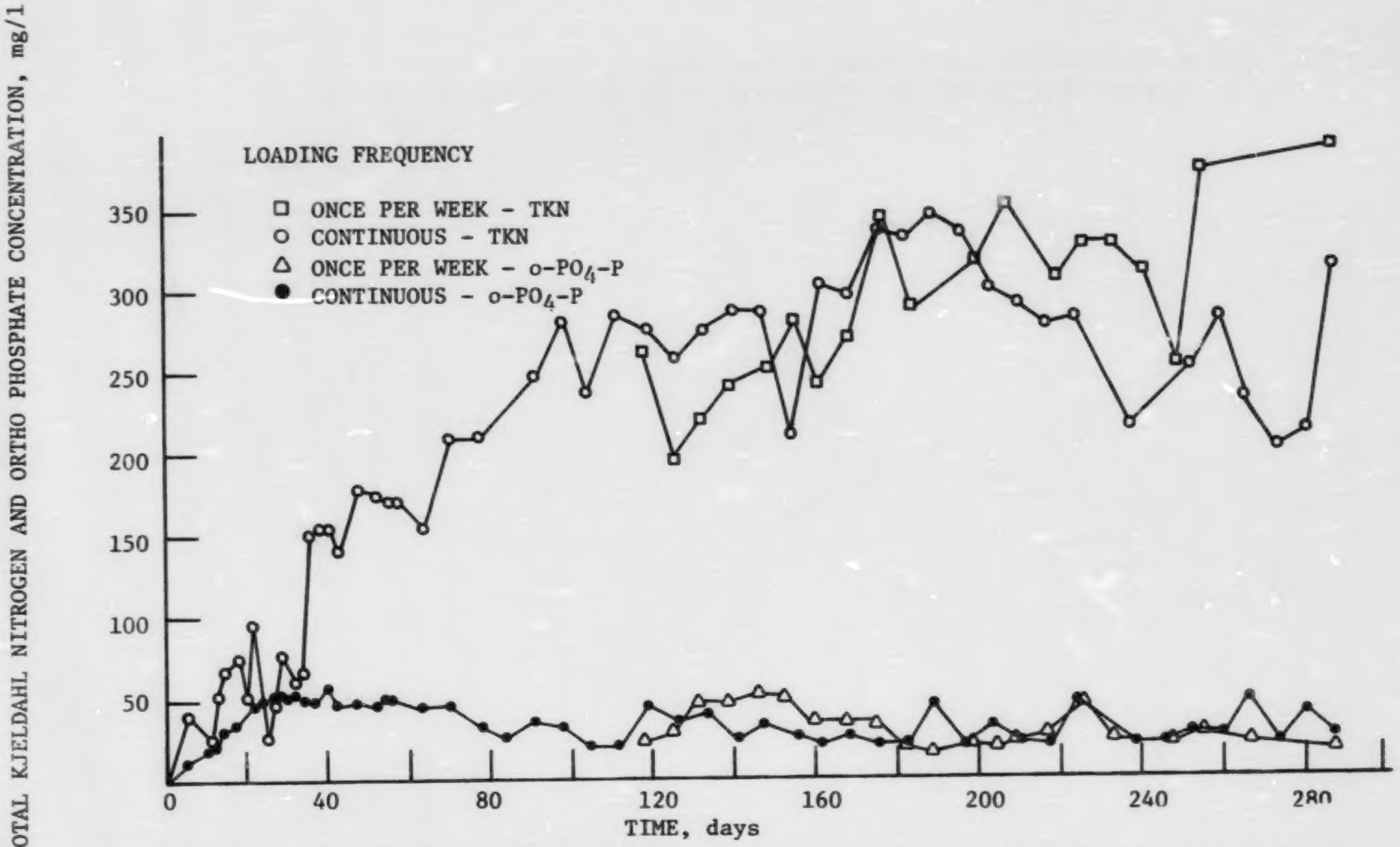


Figure 27. Supernatant TKN and o-PO_4-P concentration changes in laboratory 14-1 reactors with the nominal reference loading rate of swine waste on a continuous or batch basis.

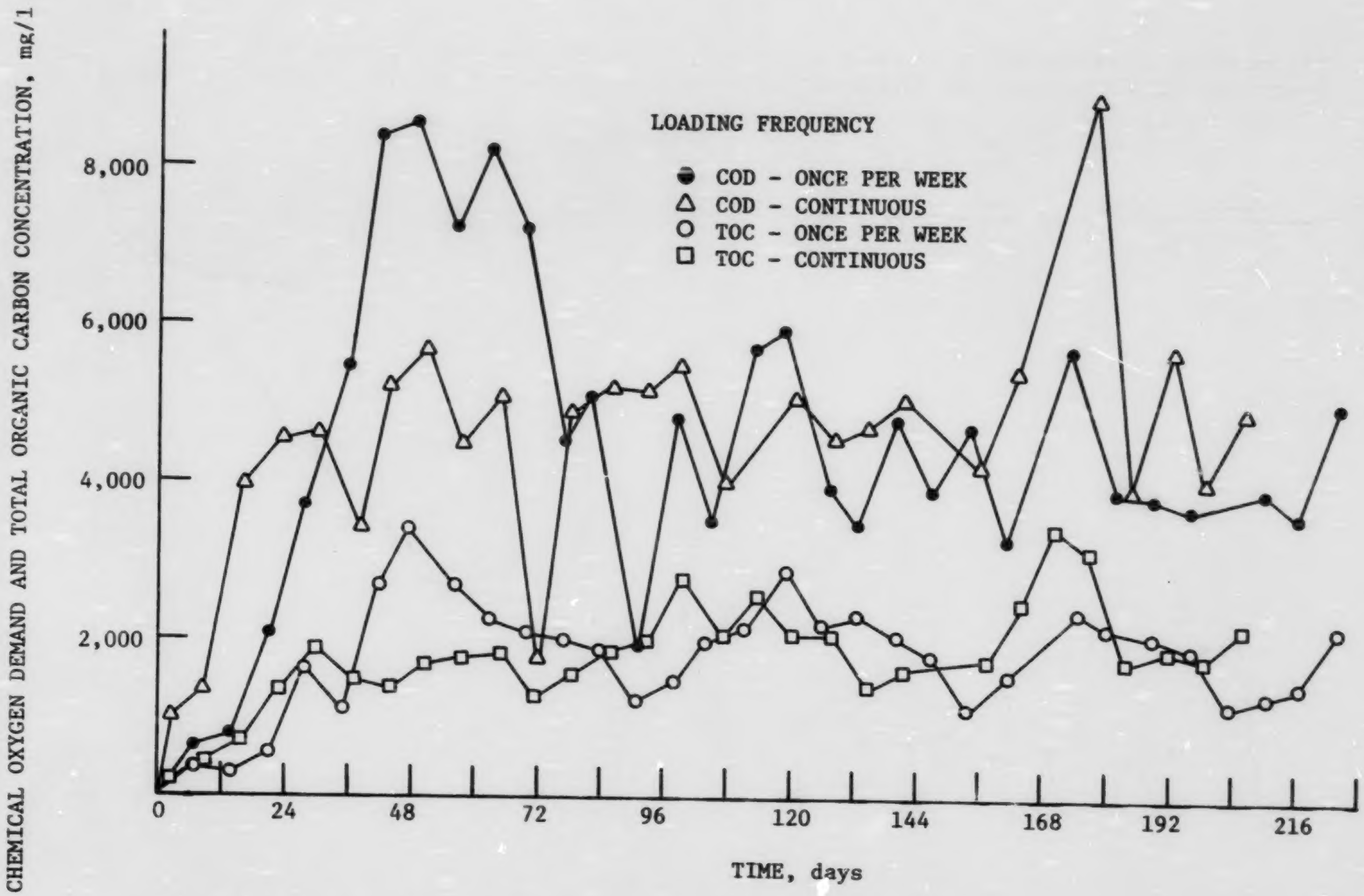


Figure 28. Supernatant COD and TOC concentration changes in laboratory 14-1 reactors with four times the nominal reference loading rate of swine waste on a continuous or batch basis.

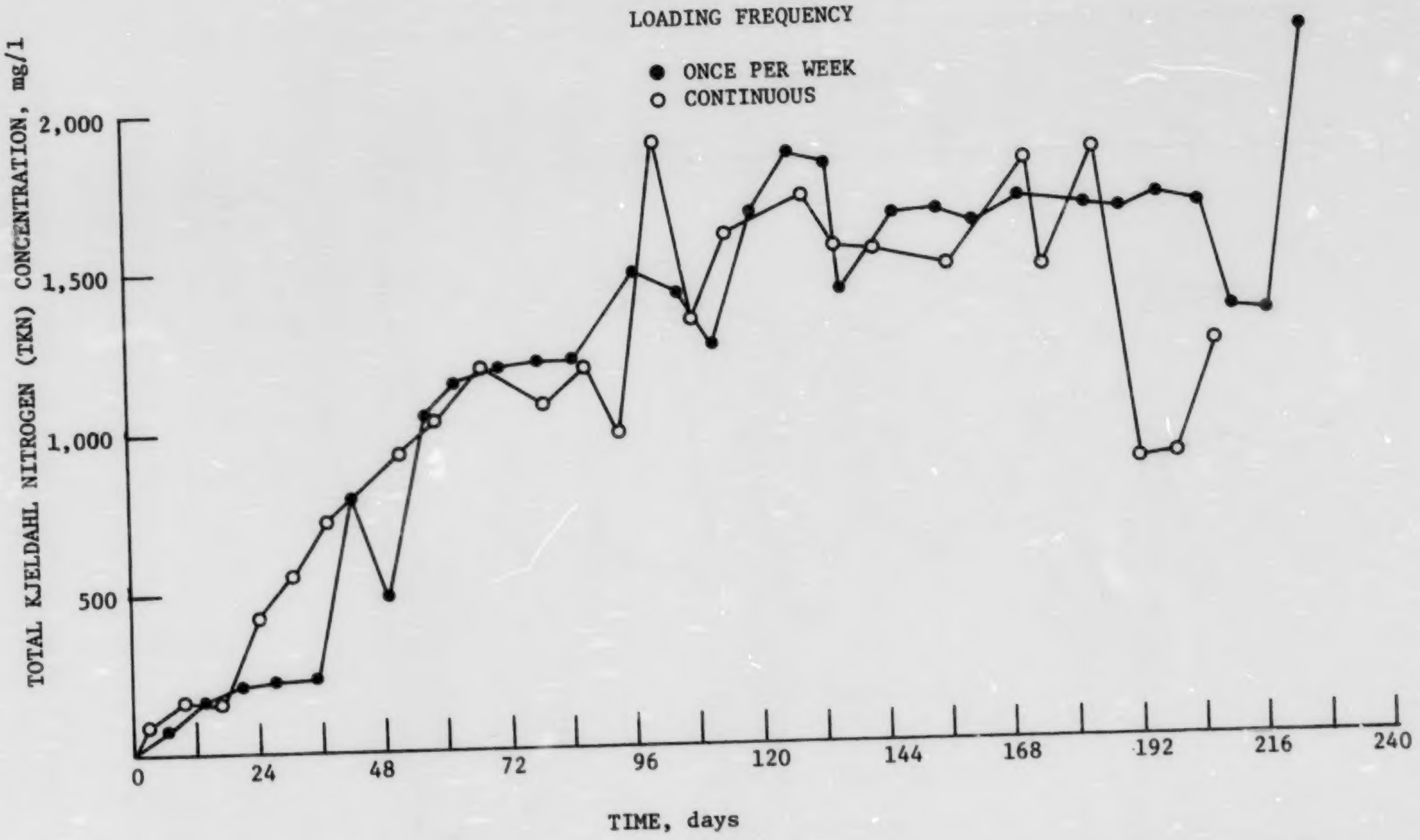


Figure 29. Supernatant TKN concentration changes in laboratory 14-l reactors with four times the nominal reference loading rate of swine waste on a continuous or batch basis.

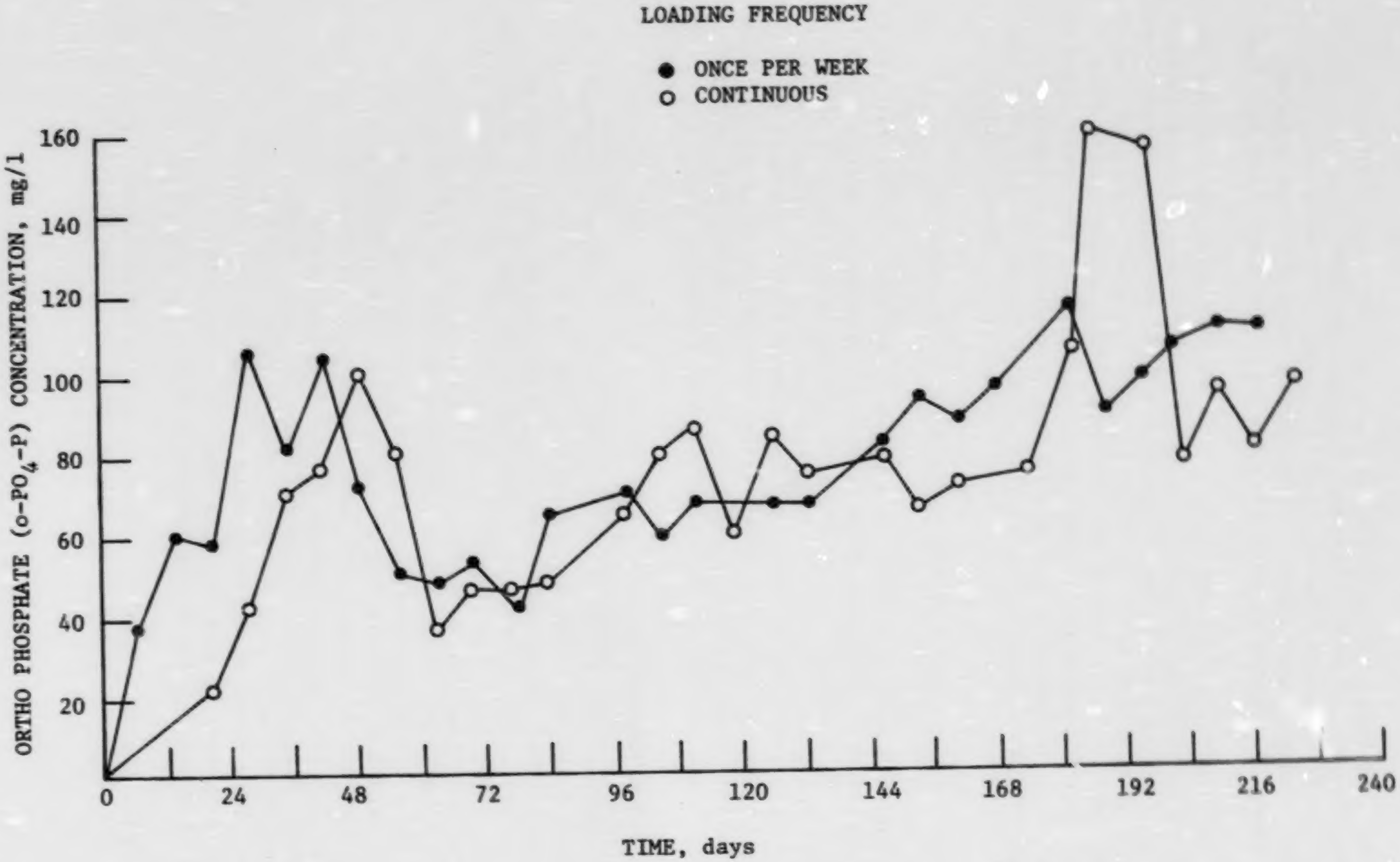


Figure 30. Supernatant o-PO$_4$-P concentration changes in laboratory 14-1 reactors with four times the nominal reference loading rate of swine waste on a continuous or batch basis.

weekly batch loading. In addition the response time to achieve a steady supernatant concentration was the same for both reactors. However, at the nominal reference loading rate the quasi-continuous unit had consistently lower supernatant concentrations than the weekly batch reactor except for ortho-phosphates which were the same, Figures 25-27.

In terms of biological activity these factors indicated that at the heavier rate there were sufficient nutrients added so that even with batch type loading the microorganisms could maintain a high viability between loading events. Thus when the next loading event occurred the viable population was sufficient to stabilize or reduce the organic matter to the same level as for the continuous loaded unit. However, at the lower loading rate the nutrient level was not sufficient to maintain the population in the batch reactor required to stabilize organic matter to the same level as with continuous reactor at the same loading rate. Experiments are underway to see if this trend is more pronounced at lower nutrient levels such as one-fourth of the nominal reference loading.

Tentative conclusions were that in a producer situation there are advantages in loading anaerobic lagoons on a continuous or nearly continuous manner. This conclusion is corroborated by data from both the laboratory and field studies. The advantages of better stabilization and improved supernatant quality may be greater if the producer is operating his lagoon with 2.3 m^3 of volume per 45-kg hog or more. This type of loading could be accomplished by having a manure pit overflow, a frequent flush system, or daily scraping or cleaning.

Loading Rate Studies-

Having determined the relative performance of 14 l laboratory reactors loaded at 4.8 and 1.2 times the reference loading rate (2.3 m^3 per 45-kg hog) additional 14 l reactors at 0.6 and 0.3 times the reference rate were begun. These rates corresponded to 3.9 and 7.8 m^3 of reactor volume per 45 kg hog. The reactors were loaded once per week and all operational and sampling procedures were the same as the previously described laboratory units. After a period of five to six weeks the TOC and COD supernatant concentrations reached the steady-state level and these data are shown in Figures 31 and 34. The total Kjeldahl nitrogen achieved a steady-state supernatant concentration in eight to nine weeks for both units, Figures 32 and 35. Supernatant phosphate concentrations are shown in Figures 33 and 36. The reduced loading rate produced effluent with a lower concentration of all parameters measured. This trend of effluent with a lower concentration being inversely dependent on loading rate was also shown with the units loaded at 4.8 and 1.2 times the reference rate.

To check sampling errors attributable to gradients which may have existed, liquid was removed from several vertical locations in the

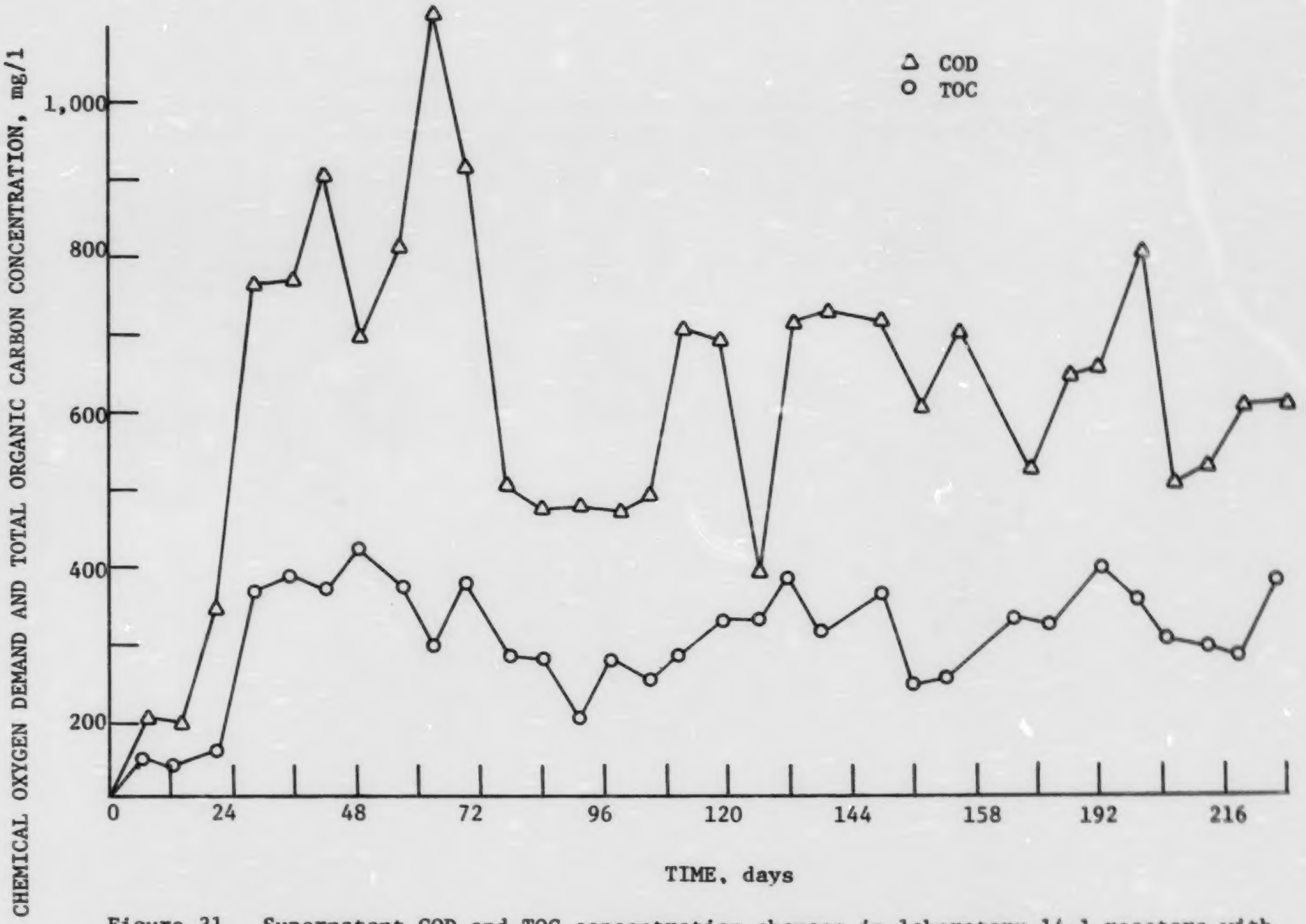


Figure 31. Supernatant COD and TOC concentration changes in laboratory 14-1 reactors with 0.6 times the reference loading rate of swine waste and once per week frequency.

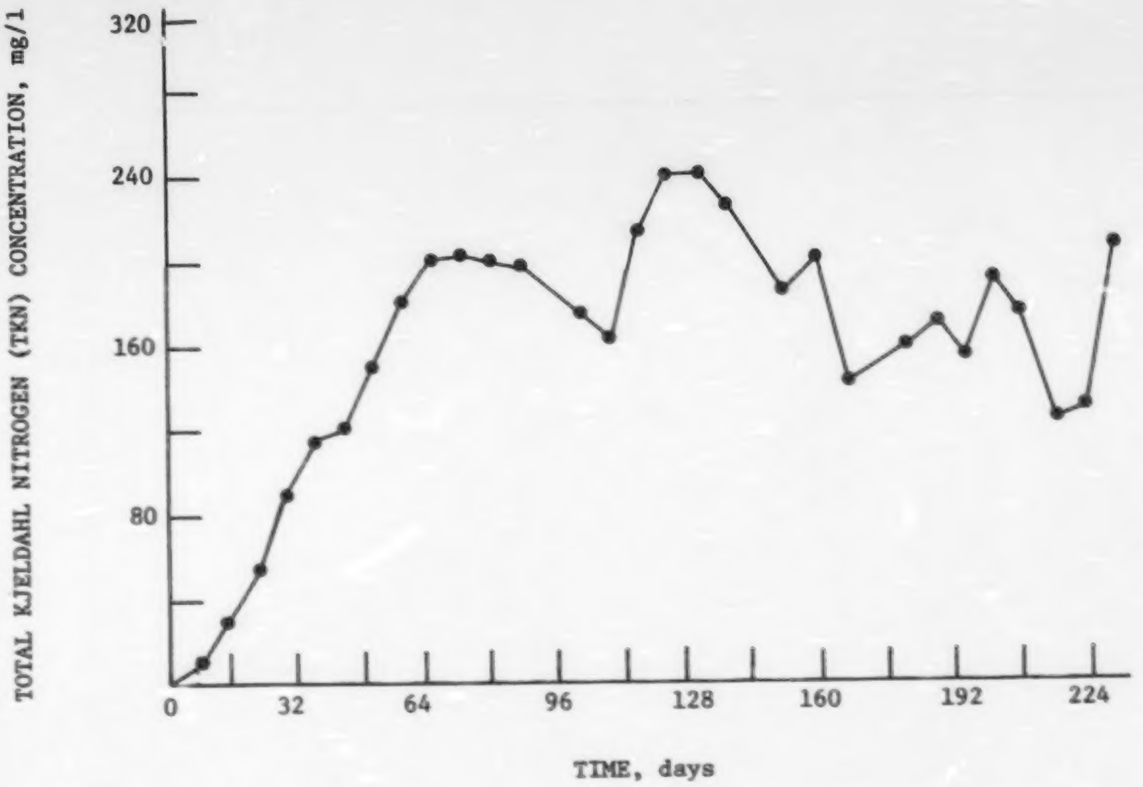


Figure 32. Supernatant TKN concentration changes in laboratory 14-1 reactors with 0.6 times the reference loading rate of swine waste and once per week frequency.

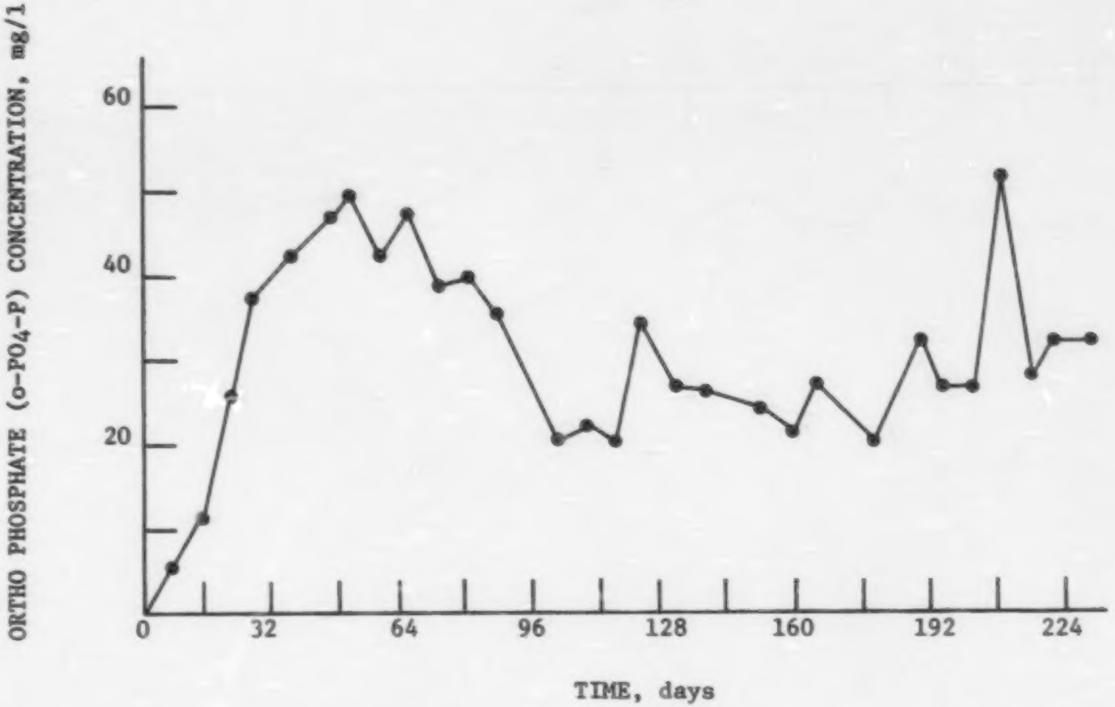


Figure 33. Supernatant o-PO$_4$-P concentration changes in laboratory 14-1 reactors with 0.6 times the reference loading rate of swine waste and once per week frequency.

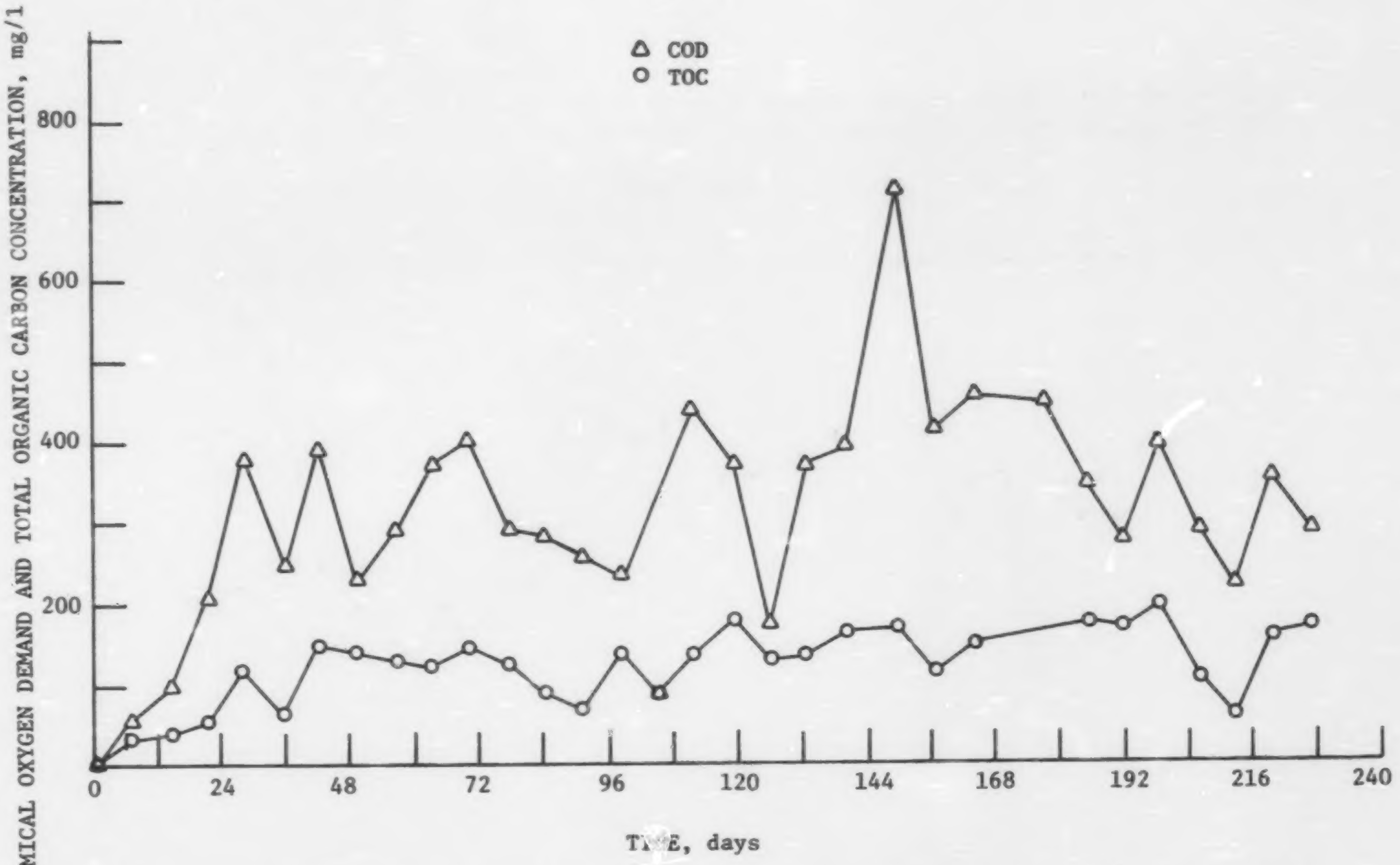


Figure 34. Supernatant COD and TOC concentration changes in laboratory 14-1 reactors with 0.3 times the reference loading rate of swine waste and once per week frequency.

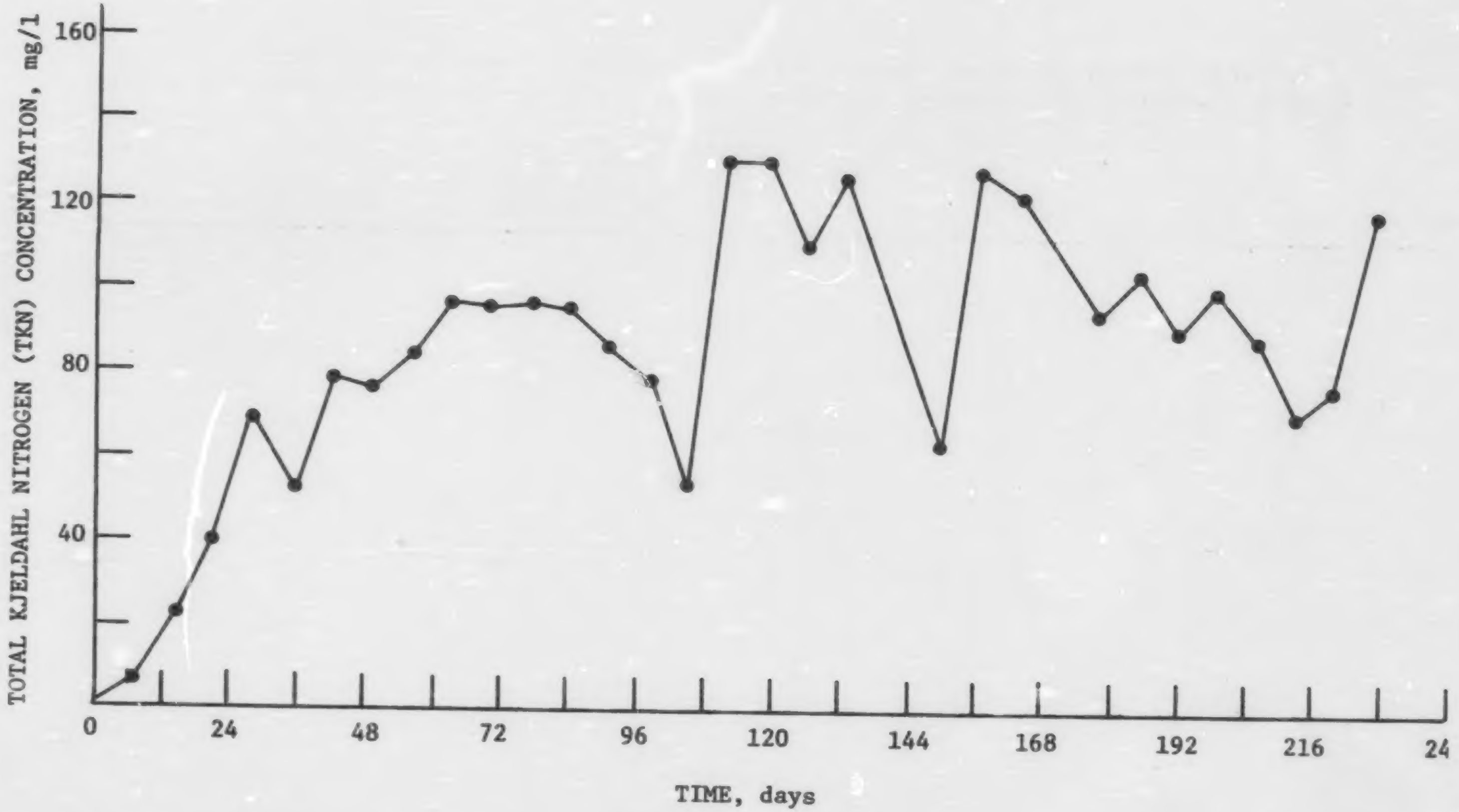


Figure 35. Supernatant TKN concentration changes in laboratory 14-1 reactors with 0.3 times the reference loading rate of swine waste and once per week frequency.

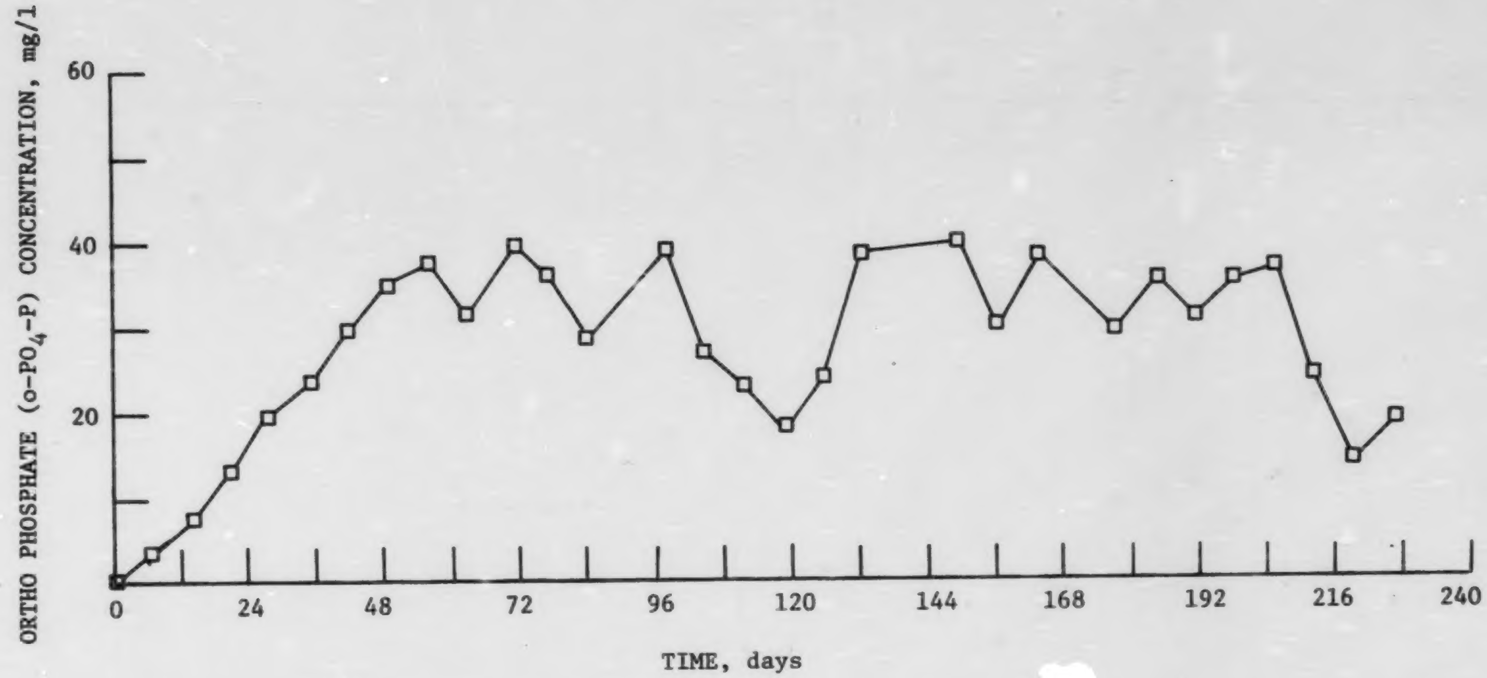


Figure 36. Supernatant o-PO$_4$-P concentration changes in laboratory 14-1 reactors with 0.3 times the reference loading rate of swine waste and once per week frequency.

14-1 reactor. These concentrations are given in Table 12. As with the Imhoff cones there was a good concentration uniformity with the exception of the sludge blanket region, Researchers describing swine waste settling[80] and dairy lagoon performance[41] have observed an interfacial zone of flocculated type material. This zone was not readily detected with employed physical sludge measurements but was probably the reason for the higher chemical concentrations near the sludge. However, the supernatant zone was uniform; hence a mid-depth sample was representative.

An extremely heavy loading rate was selected to complete the upper loading range for the 14 1 laboratory reactors. This rate was 10.8 times the reference loading which is equivalent to a volume of 0.21 m^3 (210 liter) per 45-kg hog for a waste strength of 40,000 mg/l COD characteristic for a waste volume of 7.5 l per 45-kg hog per day. Thus the residence time was approximately 28 days. The supernatant concentrations of TOC, TKN, and o-PO_4-P, Figures 37 and 38, were approximately equal to the raw waste values. These levels indicated that there was only minimal settling and biological activity and that the anaerobic system served primarily as a storage vessel. As discussed in a later section, a unit with such a heavy loading rate would be expected to reach the approximate feed concentration in about 12-16 weeks as verified by Figures 37 and 38 showing that in fact steady conditions were reached in about 11 or 12 weeks. The raw waste-like characteristics of the supernatant were also verified by visual observations and the high analytical variability, resulting in part due to sampling difficulties with these thick type slurries.

After initial data were taken on this reactor, a sealed top was installed with a tube leading to a gas collection device. This unit then simulated a methane producing digester at constant laboratory temperature (25° C). Steady-state gas generation was 3.6 l/day with a composition of 50 percent CH_4 and 40 percent CO_2. Gas evolution represented 22 percent of the input carbon based upon mass balances for carbon content of collected gas and TOC of waste input (55.6 g/wk).

Efficiency of a lagoon could be calculated in several ways depending upon the assumptions used. If one assumes that sludge buildup is very slow and thus will not have to be removed, then lagoon efficiency is related to the ratio of effluent concentration or supernatant quality to the influent quality. This efficiency can be expressed for each chemical parameter. The assumption of slow sludge buildup is based on general experience and appeared to be reasonable for swine. For example, the sludge depth of about 0.6 m in one North Carolina State University swine lagoon operating near the reference loading rate for 13 years has been judged to represent a very slow buildup rate.

The lagoon efficiency for the four loading rates in the laboratory reactors are thus calculated for each parameter as follows:

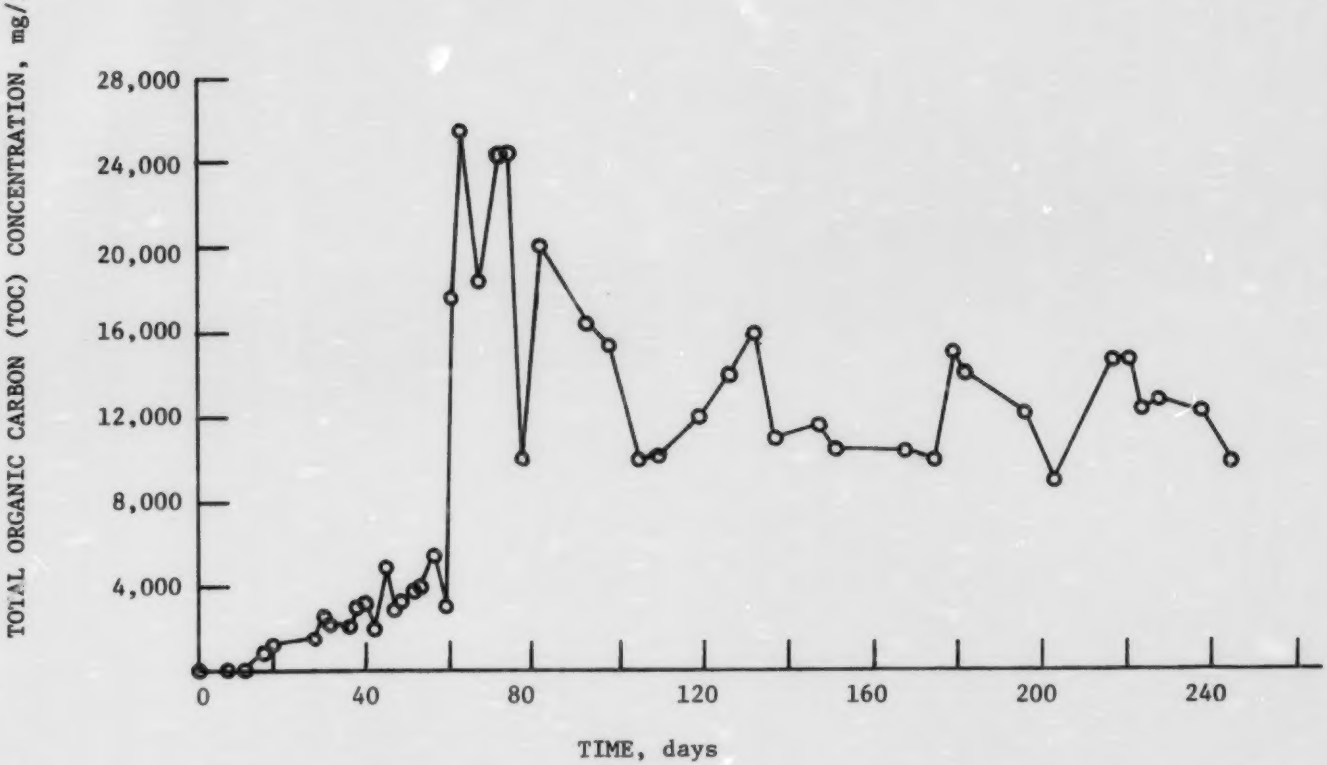


Figure 37. Supernatant TOC concentration changes in laboratory 14-1 reactors with 10.8 times the reference rate of swine waste.

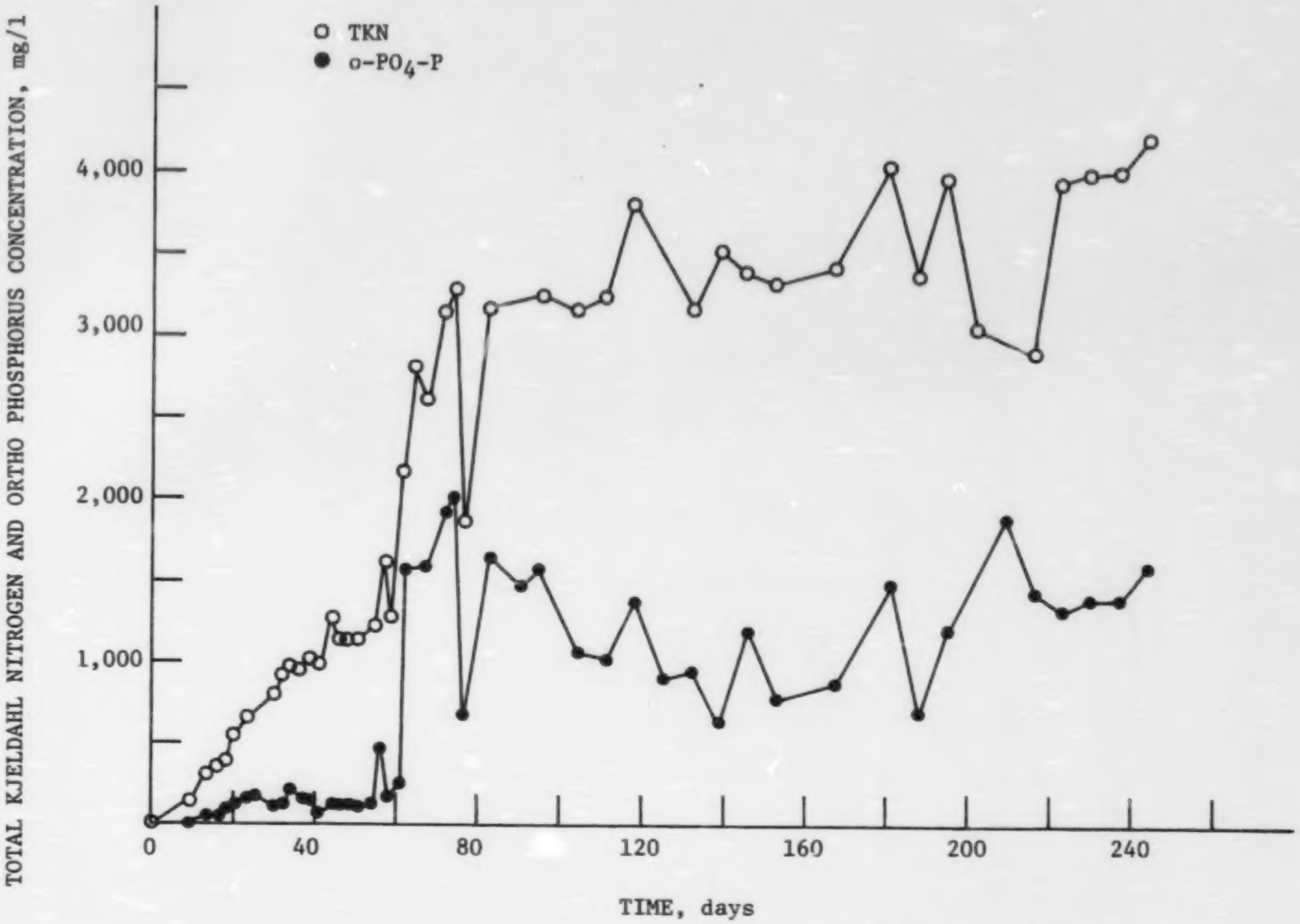


Figure 38. Supernatant TKN and o-PO$_4$-P concentration changes in laboratory 14-1 reactors with 10.8 times the reference rate of swine waste.

Table 18. REMOVAL EFFICIENCIES (EQUATION 2) OF VARIOUS POLLUTIONAL PARAMETERS FROM 14-l LABORATORY REACTOR LOADED WITH SWINE WASTES

Input to all reactors:
COD - 40,000 mg/l
TOC - 15,000 mg/l
TKN - 2,500 mg/l
$o\text{-}PO_4\text{-}P$ - 800 mg/l

14-l reactors				
Loading rate (fraction or multiple of reference rate)	Loading Frequency	Parameter	Effluent, mg	Removal efficiency, %
.25	once per week	COD	350	99
		TOC	160	99
		TKN	100	96
		$o\text{-}PO_4\text{-}P$	35	96
.5	once per week	COD	500	99
		TOC	275	98
		TKN	200	92
		$o\text{-}PO_4\text{-}P$	30	96
1	once per week	COD	1,200	97
		TOC	500	97
		TKN	400	84
		$o\text{-}PO_4\text{-}P$	30	96
1	continuous	COD	1,000	98
		TOC	400	97
		TKN	275	89
		$o\text{-}PO_4\text{-}P$	25	97
4	continuous	COD	4,500	88
		TOC	2,200	85
		TKN	1,500	40
		$o\text{-}PO_4\text{-}P$	90	89
4	once per week	COD	4,000	90
		TOC	2,000	87
		TKN	1,700	32
		$o\text{-}PO_4\text{-}P$	110	86

Table 19. REMOVAL EFFICIENCIES OF VARIOUS POLLUTIONAL PARAMETERS FROM IMHOFF CONE LABORATORY REACTORS LOADED WITH SWINE WASTE

Input to all reactors:
COD - 40,000 mg/1
TOC - 15,000 mg/1
TKN - 2,500 mg/1
$o\text{-}PO_4\text{-}P$ - 800 mg/1

Imhoff Cones				
Loading rate (multiple of reference rate)	Loading frequency	Parameter	Effluent, mg/1	Removal Efficiency, %
1	once per week	COD	1,250	97
		TOC	500	97
		TKN	150	94
		$o\text{-}PO_4\text{-}P$	60	90
1	thrice per week	COD	1,400	97
		TOC	500	97
		TKN	150	94
		$o\text{-}PO_4\text{-}P$	60	90
1	once per week	COD	1,000	98
		TOC	450	97
		TKN	200	92
4	once per week	COD	2,300	94
		TOC	900	94
		TKN	900	64

$$\text{efficiency} = \frac{\text{influent concentration} - \text{effluent concentration}}{\text{influent concentration}} \qquad (2)$$

Results for the 14-1 reactors are shown in Table 18 and for the Imhoff cones in Table 19.

It was quite evident that when calculated in this manner, the removal efficiencies for all parameters were quite high with the highest efficiencies being for the organic carbon species. The percentage of TOC and COD in the effluent increased at the higher loading rates with the removals being only 85 - 95 percent at the reference loading rate or lower. However, at the four times reference rate, the nitrogen removal was much lower, 35 - 65 percent.

Summarizing removal efficiencies based on laboratory experiments, it was clear that, at the reference loading rate or lower, the percentage of input COD, TOC, TKN, and o-PO_4-P in the effluent was very low. Correspondly, 90 percent and often more than 95 percent removals were obtained in these anaerobic systems. At higher loading rates, the phosphate and nitrogen removal became considerably lower. However, it should be noted that even with about 95 percent removals in the laboratory tests, the effluent levels of COD, TOC, TKN, and o-PO_4-P were 1,500, 500, 400, and 40 mg/l, respectively. In comparison to discharge criteria and even certain municipal and industrial raw waste streams, this effluent was very strong. This emphasized the basis for regulations specifying no discharge of effluents from anaerobic swine lagoons.

FIELD PILOT-SCALE EXPERIMENTS

Unaerated Anaerobic Reactors

Field pilot-scale experimentation was initiated to allow verification of laboratory results and screening of variables under actual field conditions without the large costs associated with full-scale studies. Field pilot-scale lagoons were constructed with 2 mm thick steel in a cylindrical shape 3.5 meters in diameter and 2.5 meters high. Overflow pipes with external gate valves were set at the 1.85 m height providing a volume of 17.5 cubic meters. The inside and outside of all the pilot lagoons were painted with primer and an epoxy paint. After two years of operation, paint peeled in some small areas where the sides were alternately exposed to air and anaerobic lagoon supernatant but no peeling has been found in continuously submerged regions. It was determined that there was little or no seepage from the reactors. The schematic and photographic representations of the field site are shown in Figures 39 and 40.

The field procedure involved once-per-week loading of raw swine waste from a manure pit under a partially slatted floor described in detail in the lagoon studies field pilot-scale experiments section. The raw waste was mixed in a 7,500-l holding tank by pump recirculation until homogenous and, if necessary, diluted with water to a 40,000 mg COD/l level. During the weekly reaction period, the overflow gate valve on each lagoon remained closed. Prior to loading, the volume of material above the overflow level was measured and samples of the supernatant taken at the .93-m depth with the APHA-type sampler. If the lagoon level was below the overflow pipe level, water was added to restore unit standard volume. These effluent or water addition volume measurements, along with on-farm precipitation and temperature records, allowed mass balance evaluation of various inputs and outflows from these pilot lagoons. After supernatant sampling, each gate valve was opened for overflow draining and then closed.

Next each lagoon received the waste input which was a constant volume since the input concentration was held relatively constant. This procedure was repeated once each week.

The reliability of complete tank mixing before and during loading and effectiveness of loading by hose discharge and manure loading tanks were determined. Results for the COD analysis, shown in Table 20, indicated that the agitation and loading system was adequate even though some unexplained slightly higher concentrations would periodically occur.

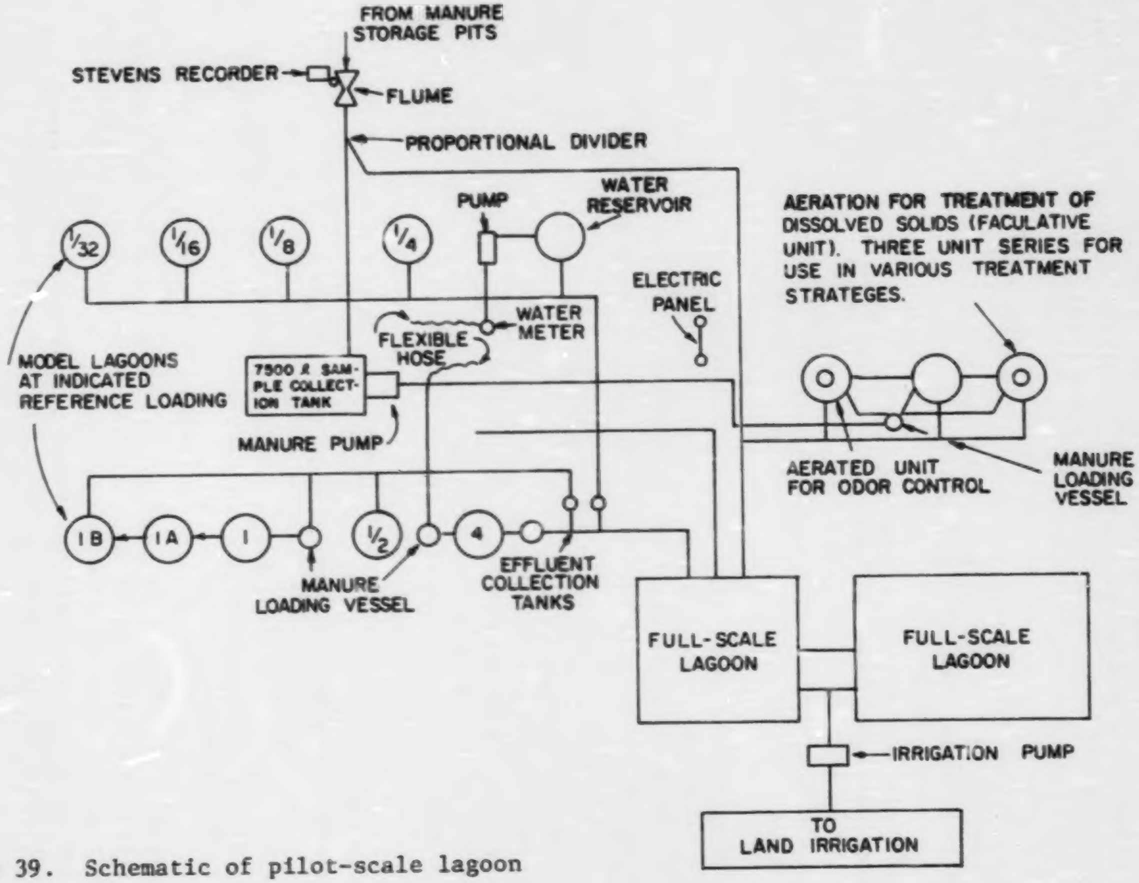

FROM MANURE STORAGE PITS
STEVENS RECORDER
FLUME
PROPORTIONAL DIVIDER
PUMP
WATER RESERVOIR
AERATION FOR TREATMENT OF DISSOLVED SOLIDS (FACULATIVE UNIT). THREE UNIT SERIES FOR USE IN VARIOUS TREATMENT STRATEGES.
1/32
1/16
1/8
1/4
ELECTRIC PANEL
WATER METER
FLEXIBLE HOSE
MODEL LAGOONS AT INDICATED REFERENCE LOADING
7500 ℓ SAMPLE COLLECTION TANK
MANURE PUMP
AERATED UNIT FOR ODOR CONTROL
MANURE LOADING VESSEL
1B
1A
1
1/2
4
MANURE LOADING VESSEL
EFFLUENT COLLECTION TANKS
FULL-SCALE LAGOON
FULL-SCALE LAGOON
IRRIGATION PUMP
TO LAND IRRIGATION

Figure 39. Schematic of pilot-scale lagoon research site.

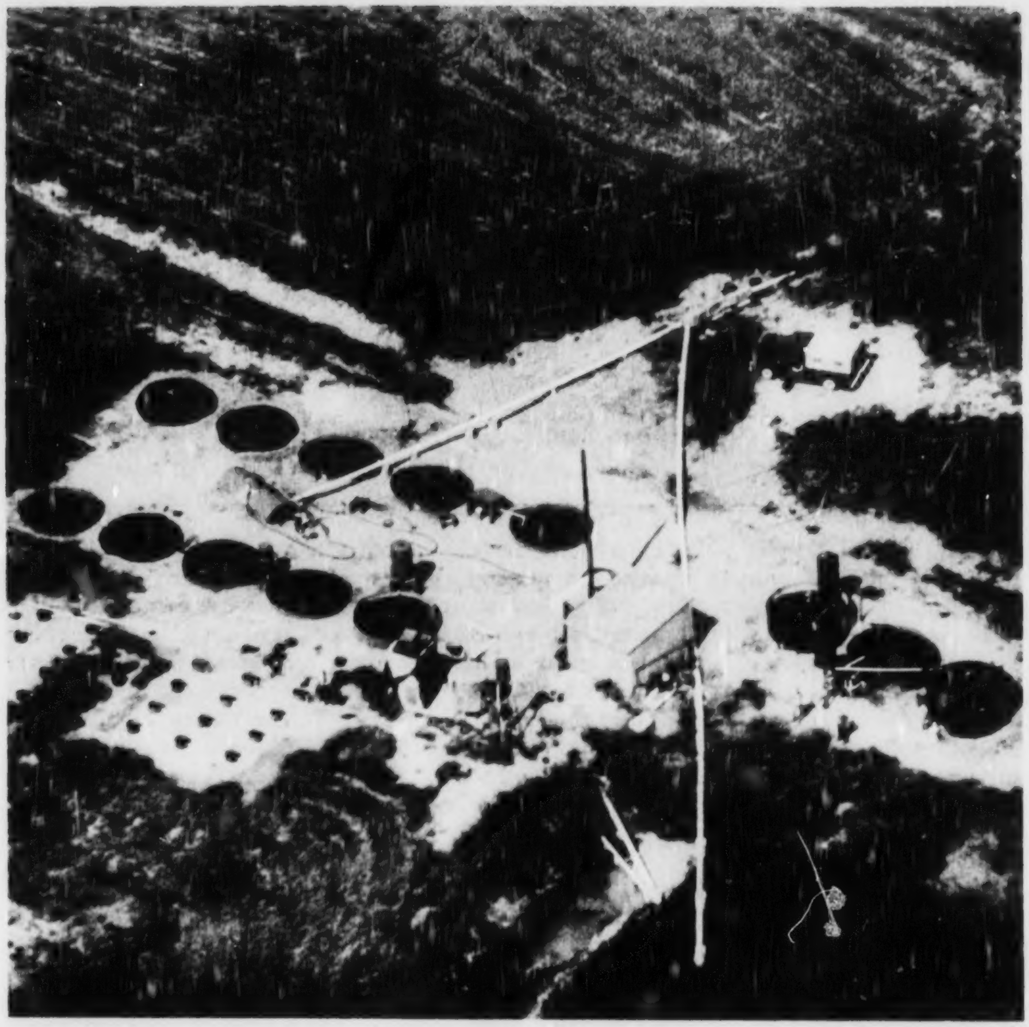


Figure 40. Photograph of pilot-scale lagoon research site.

Table 20. UNIFORMITY OF RAW SWINE WASTE DURING AGITATION AND LOADING OF FIELD PILOT-SCALE LAGOONS

COD concentration, mg/l	Sample description
43,100	hose discharge recycling to mixing tank
41,100	hose discharge to first unit
36,700	loading tank discharge to heaviest loaded reactor, start of loading
39,400	loading tank discharge to heaviest loaded reactor, end of loading
48,900	hose discharge to next to the last pilot lagoon
45,600	hose discharge to last pilot lagoons

Loading of the field pilot-scale or model lagoons began on July 11, 1972, with swine wastes stored in nearby manure pits and fresh manure was used since October 31, 1972. Raw waste was continuously characterized and loading rates adjusted as necessary to conform with the desired pre-experiment rates. The loads to each reactor were based on multiples or fractions of the reference rate (Table 4) of 2.3 m^3 of lagoon volume per 45-kg hog, Table 21. Additionally, two pilot-scale tanks were established to give series lagoon treatment to the effluent from the unit receiving the reference loading rate. These were referred to as the second lagoon in series (1A) and the third lagoon in series (1B).

For the period January 16, 1973, to April 1, 1973, the waste material was fairly constant at 40,000 mg COD/1, the expected value for a total daily waste volume of 7.5 1 from a 45-kg hog.

However, during the spring and summer, the increased use of malfunctioning foggers and waterers prevented the maintenance of a high concentration waste. This period was characterized by a waste in the range of 10,000 - 25,000 mg COD/1. The small lagoon freeboard available prohibited loading at a constant magnitude of COD per week when the waste input was so dilute due to excessive water wastage. Thus, a constant feed volume was added but it was impossible to maintain a uniform waste concentration during this period. Finally in the fall of 1973, a source of concentrated waste was secured and, as needed, diluted to approximately 40,000 mg COD/1.

Table 21. SWINE WASTE LOADING RATE OF FIELD PILOT-SCALE UNITS

Multiple or fraction of reference rate	Swine waste volume added per week, l	kg COD/week/m^3 (40,000 mg COD/l)	m^3 lagoon volume per 45-kg hog
4	840	3.64	0.6
1	420	0.91	2.3
1A	overflow from 1	--	--
1B	overflow from 1A	--	--
1/2	210	0.45	4.6
1/4	105	0.23	9.2
1/8	52	0.12	18.4
1/16	26	0.055	36.8
1/32	13	0.028	73.6

Lagoon Supernatant Concentrations

The supernatant concentrations for the model units are plotted in Figures 41-58. These data are averages of the supernatant concentration over successive two-week intervals after attainment of the more concentrated waste (October, 1973). Hence, the lower initial concentration reflected the antecedent period of dilute waste input.

After the attainment of the more uniform concentrated raw waste (October, 1973) all of the pilot-scale lagoons attained a steady-state concentration during the late winter and early spring period. The judgement of the steady-state value was difficult because lagoon temperature changes with climate cycles affected reaction dynamics and thus supernatant concentration. The steady-state or uniform concentration level was more

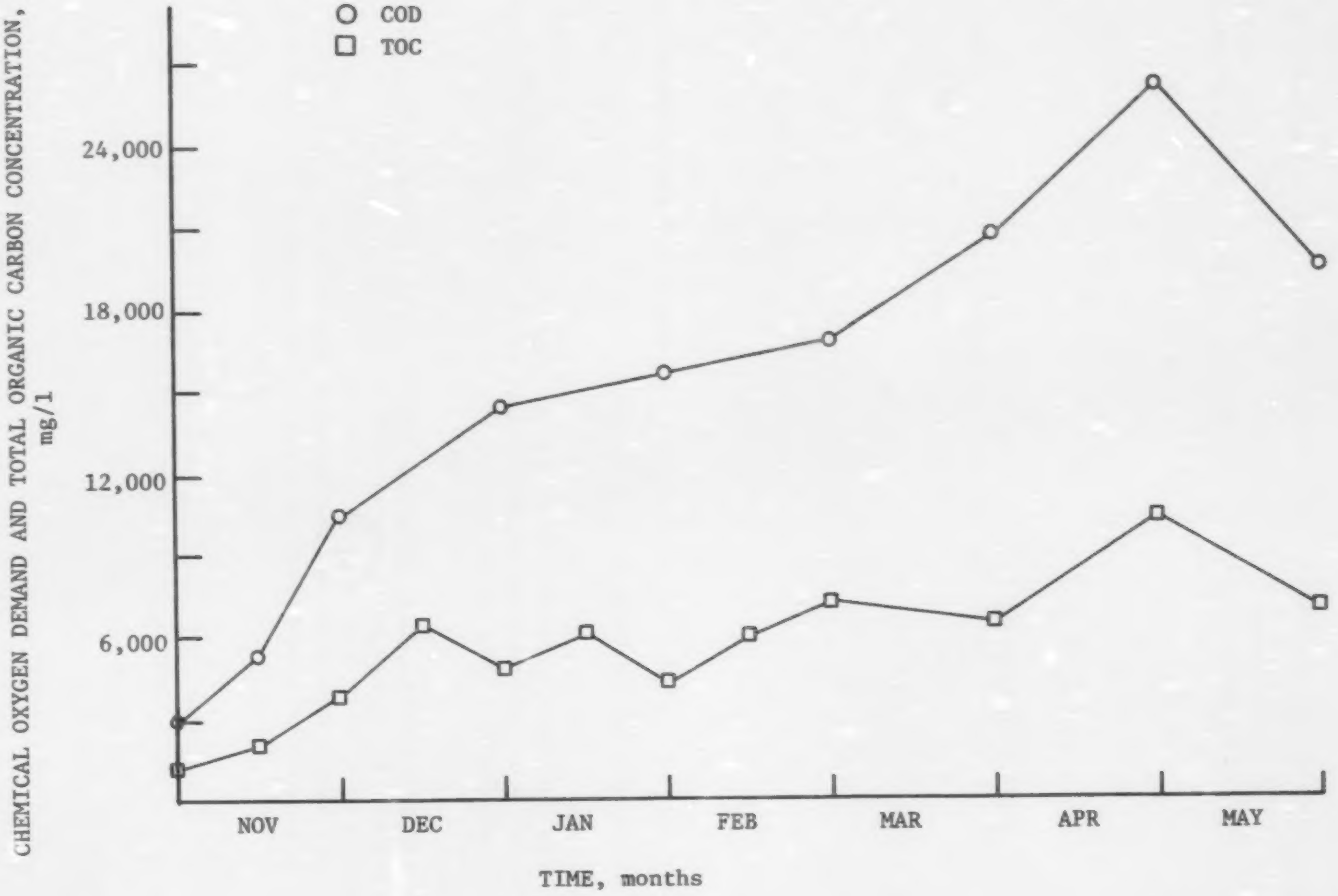


Figure 41. Supernatant COD and TOC concentration changes (two-week averages) in field pilot-scale lagoons loaded once per week at four times the reference rate for swine wastes.

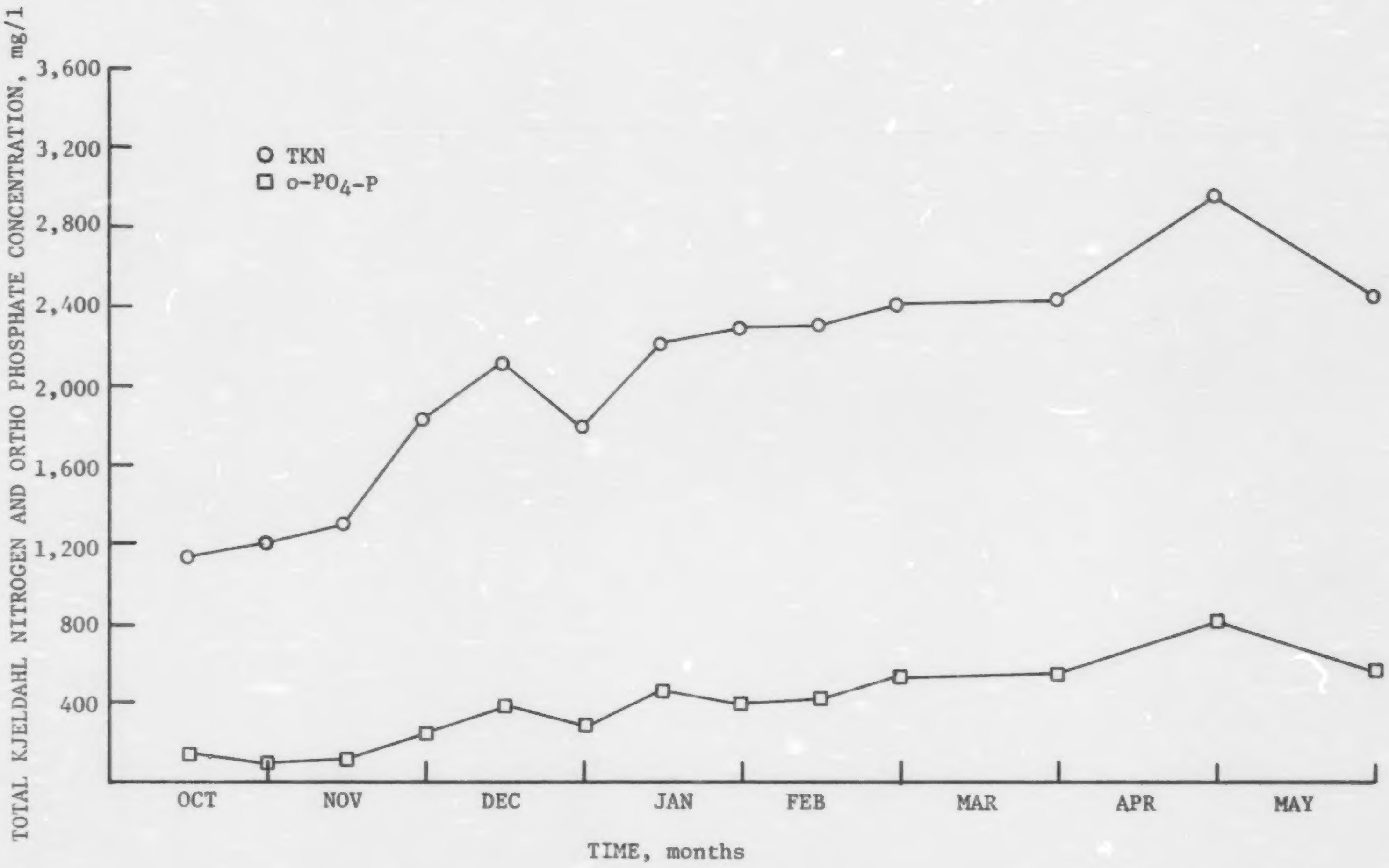


Figure 42. Supernatant TKN and o-PO$_4$-P concentration (two-week averages) in field pilot-scale lagoons loaded once per week at four times the reference rate for swine wastes.

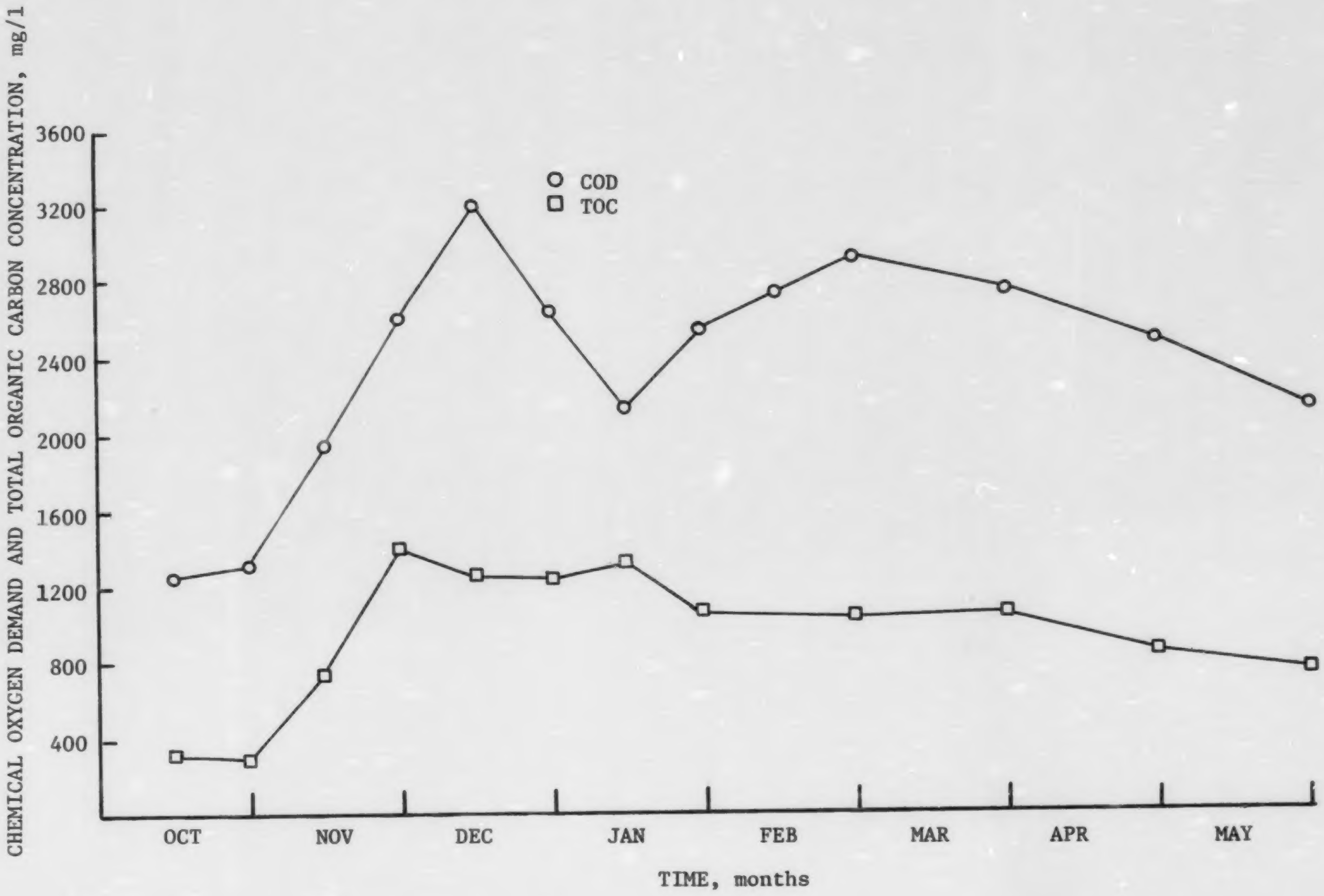


Figure 43. Supernatant COD and TOC concentration changes (two-week averages) in field pilot-scale lagoons loaded once per week at the reference rate for swine wastes.

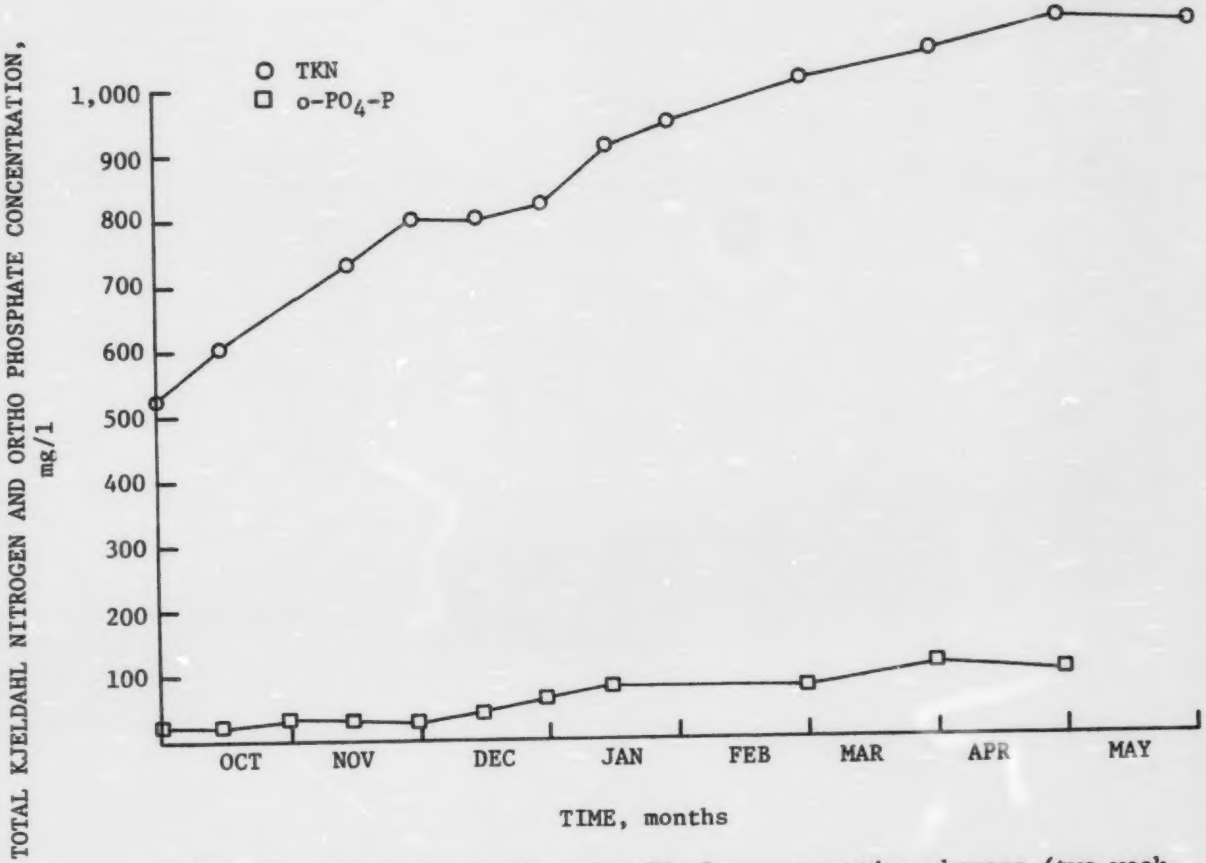


Figure 44. Supernatant TKN and o-PO$_4$-P concentration changes (two-week averages) in field pilot-scale lagoons loaded once per week at the reference rate for swine wastes.

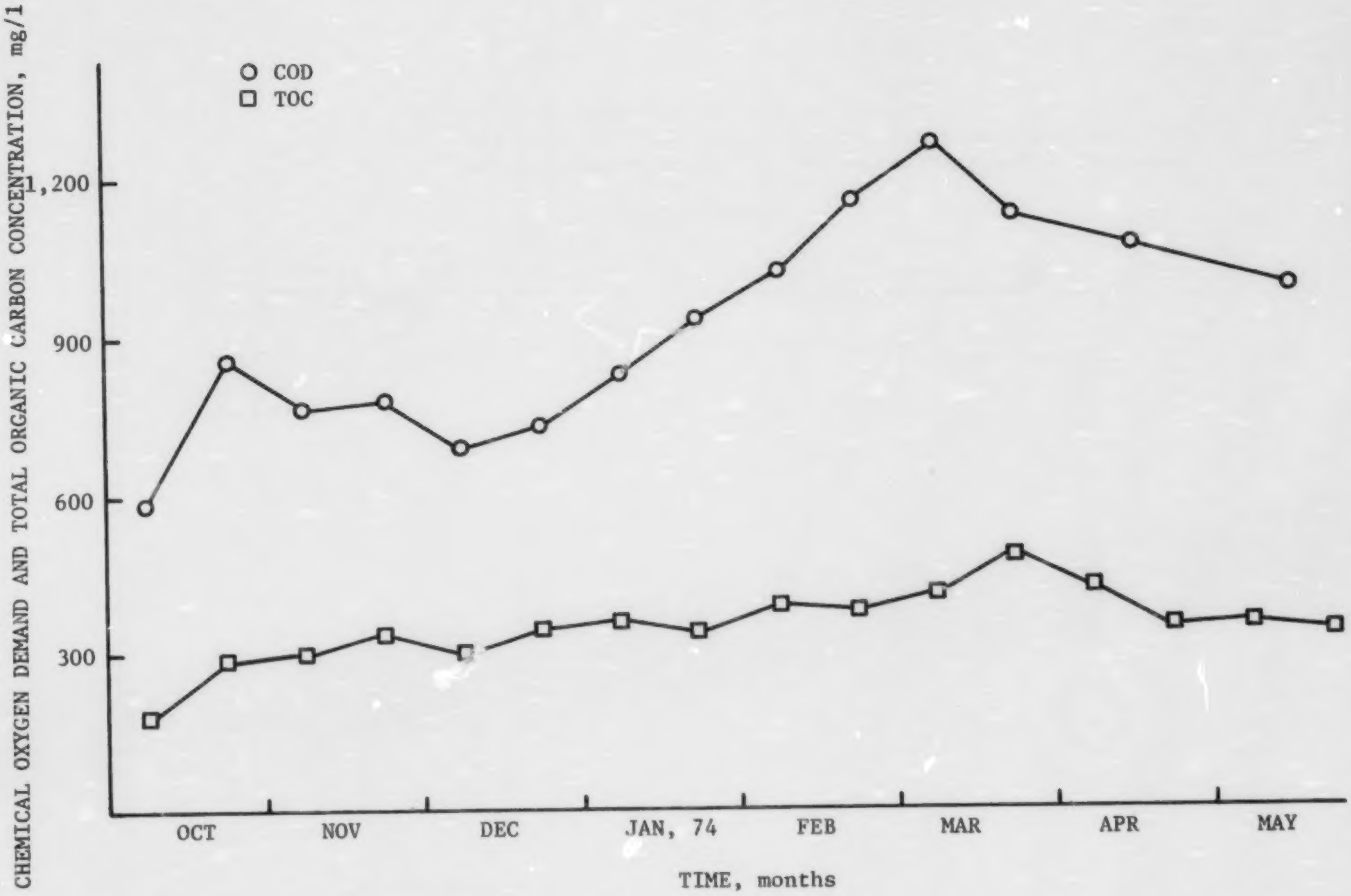


Figure 45. Supernatant COD and TOC concentration changes (two-week averages) in field pilot-scale lagoon receiving effluent from lagoon loaded once per week at reference rate for swine wastes.

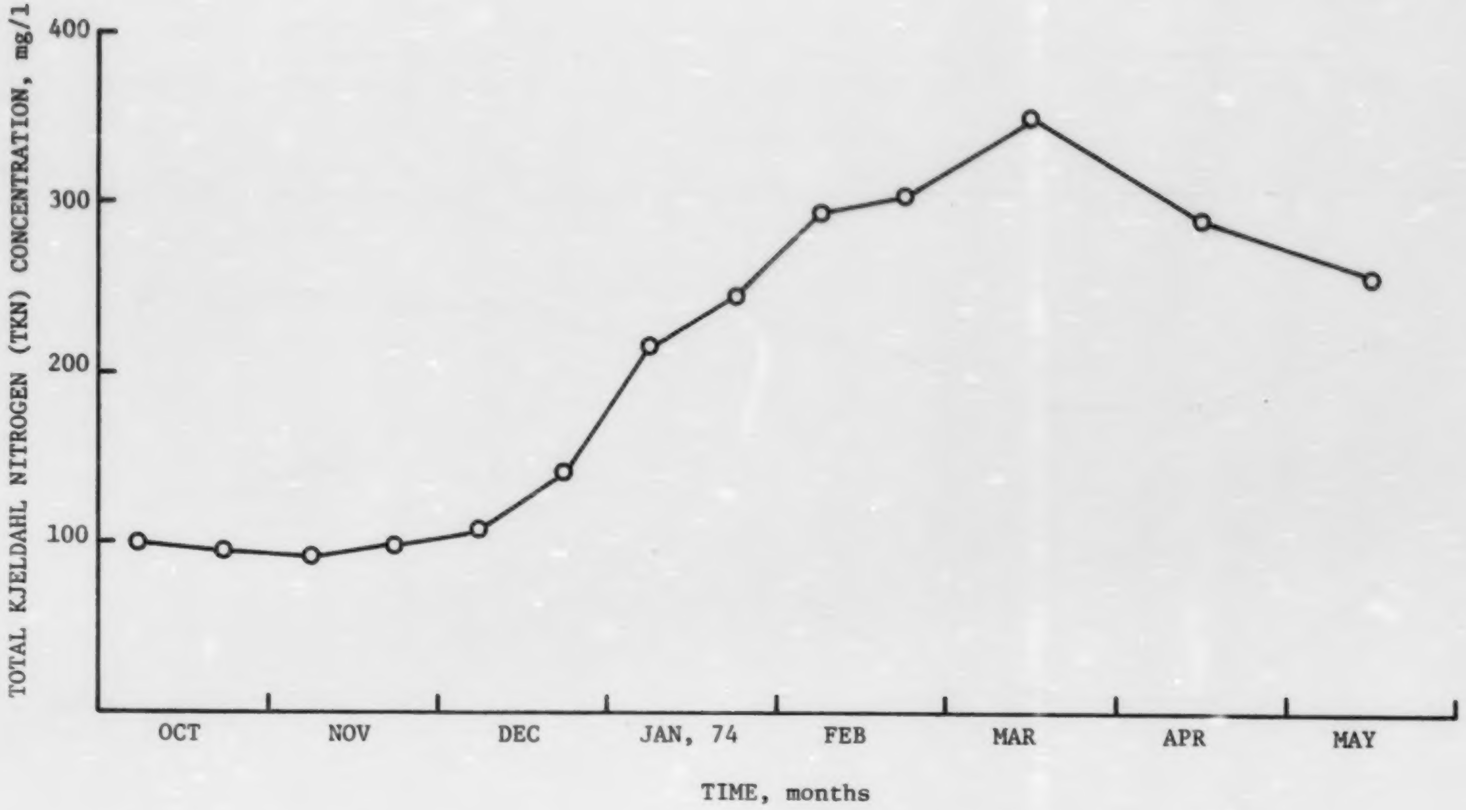


Figure 46. Supernatant TKN concentration changes (two-week averages) in field pilot-scale lagoon receiving effluent from lagoon loaded once per week at reference rate for swine wastes.

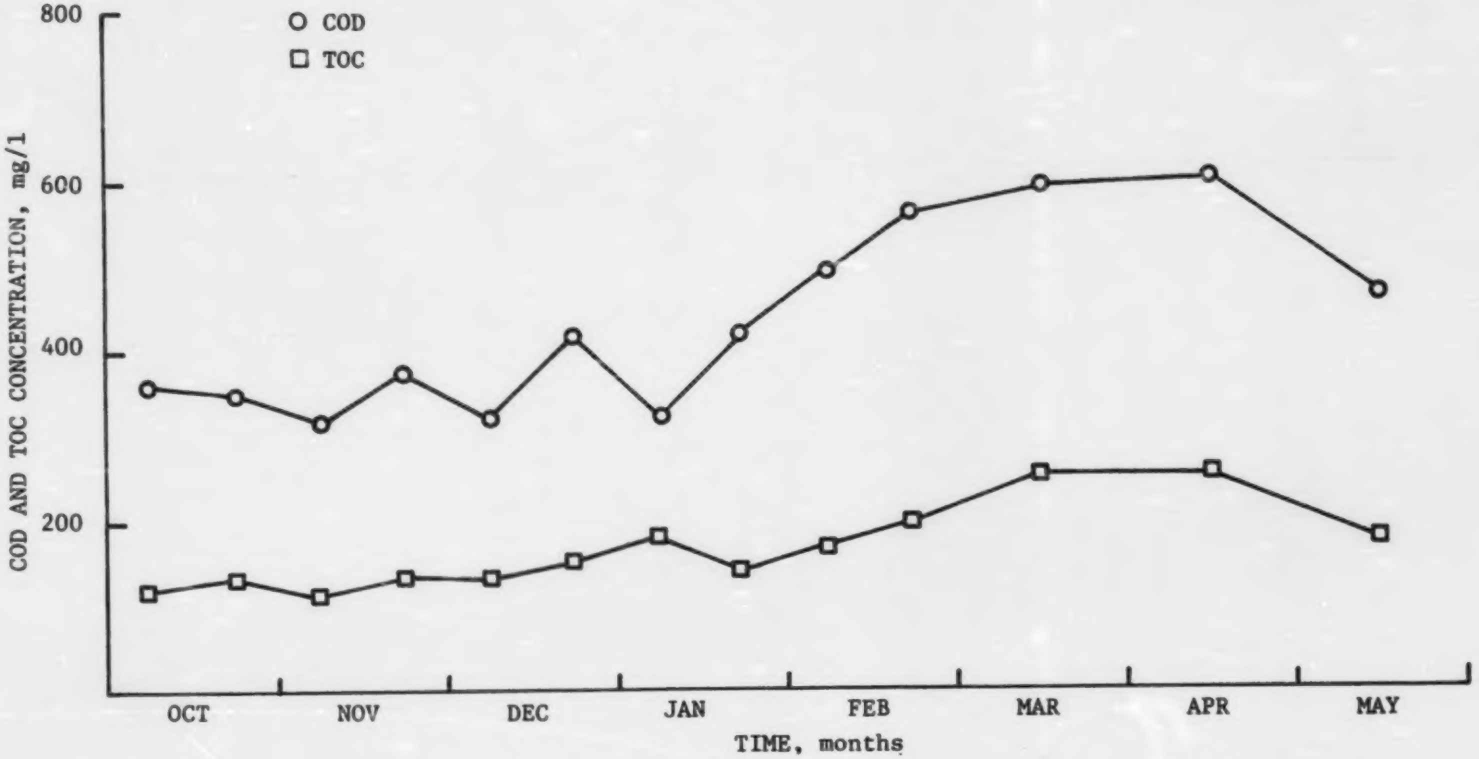


Figure 47. Supernatant COD and TOC concentration changes (two-week averages) in third lagoon of three-unit series with the first lagoon of this field pilot-scale series loaded once per week at the reference rate for swine waste.

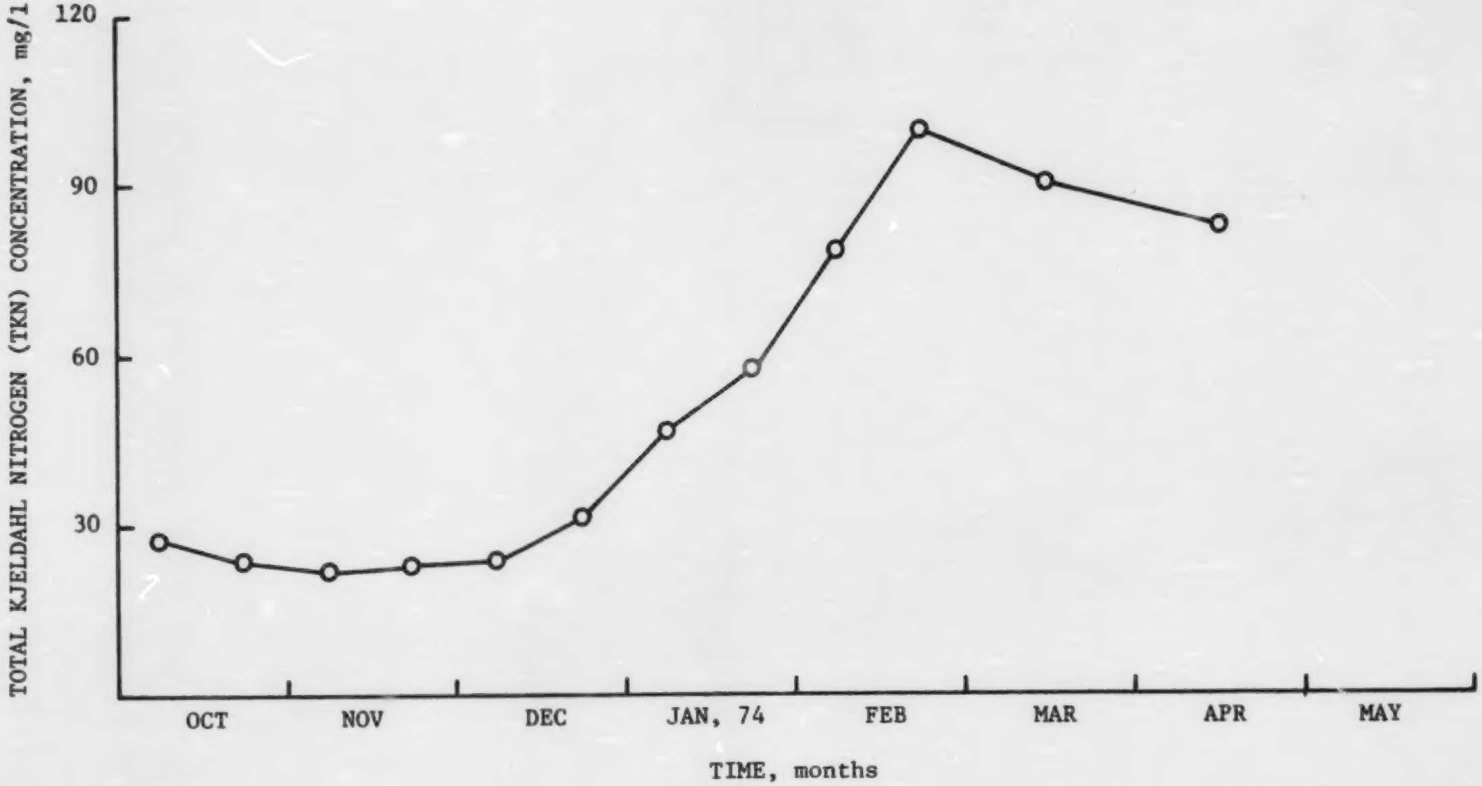


Figure 48. Supernatant TKN concentration changes (two-week averages) in third lagoon of three-unit series with the first lagoon of this field pilot-scale series loaded once per week at the reference rate for swine waste.

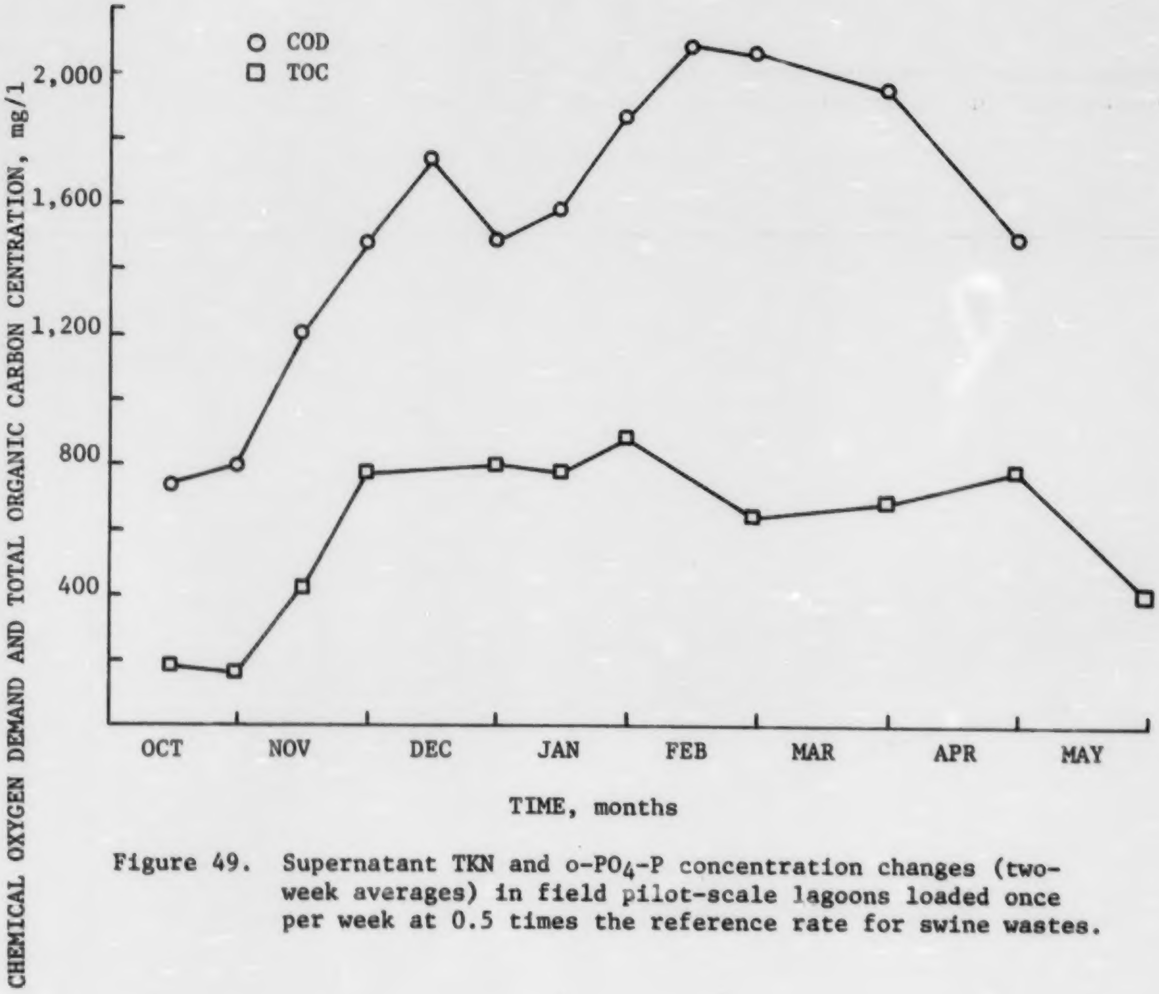


Figure 49. Supernatant TKN and o-PO_4-P concentration changes (two-week averages) in field pilot-scale lagoons loaded once per week at 0.5 times the reference rate for swine wastes.

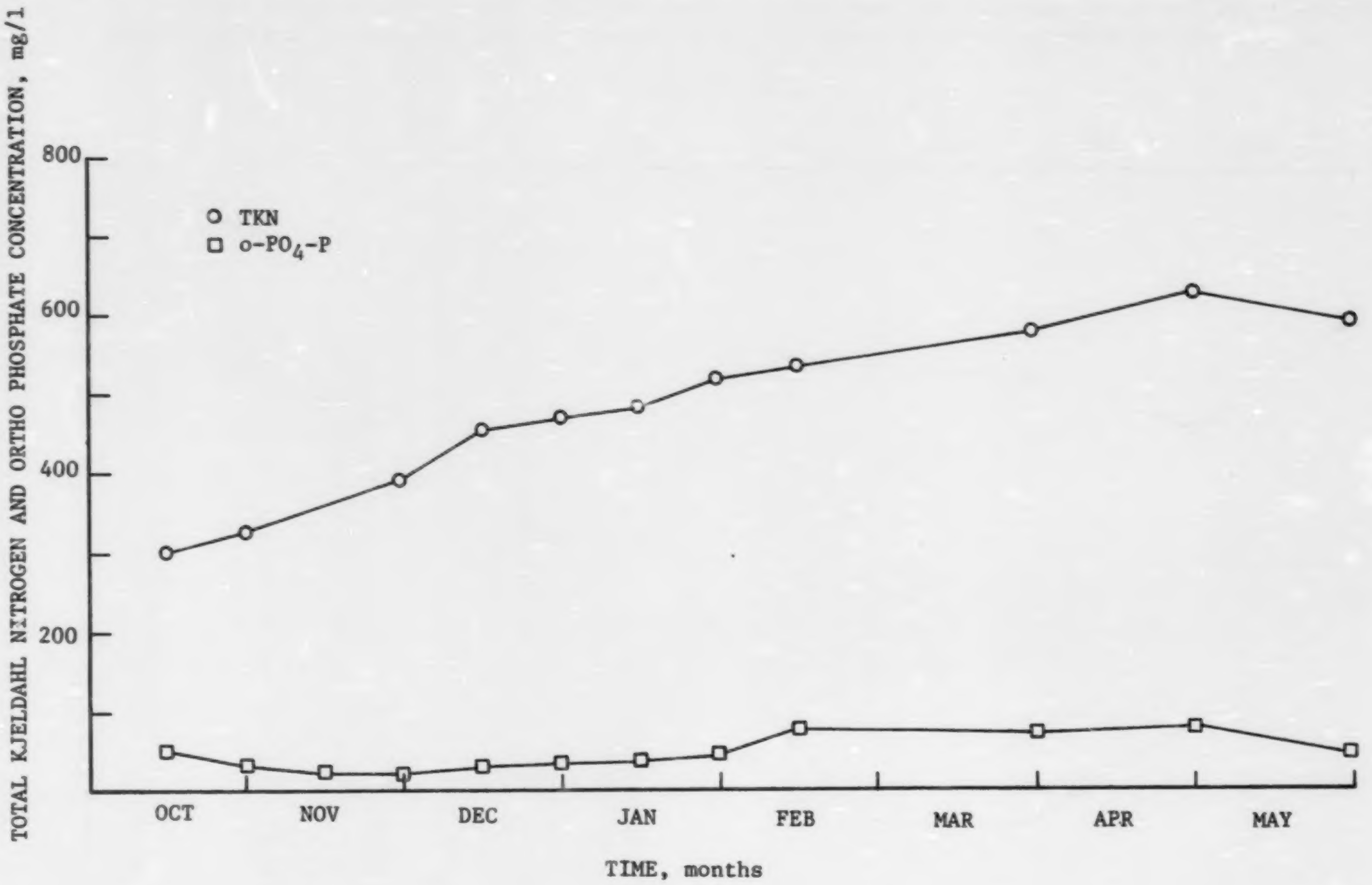


Figure 50. Supernatant TKN and o-PO$_4$-P concentration changes (two week averages) in field pilot scale lagoons loaded once per week at 0.5 times the reference rate for swine wastes.

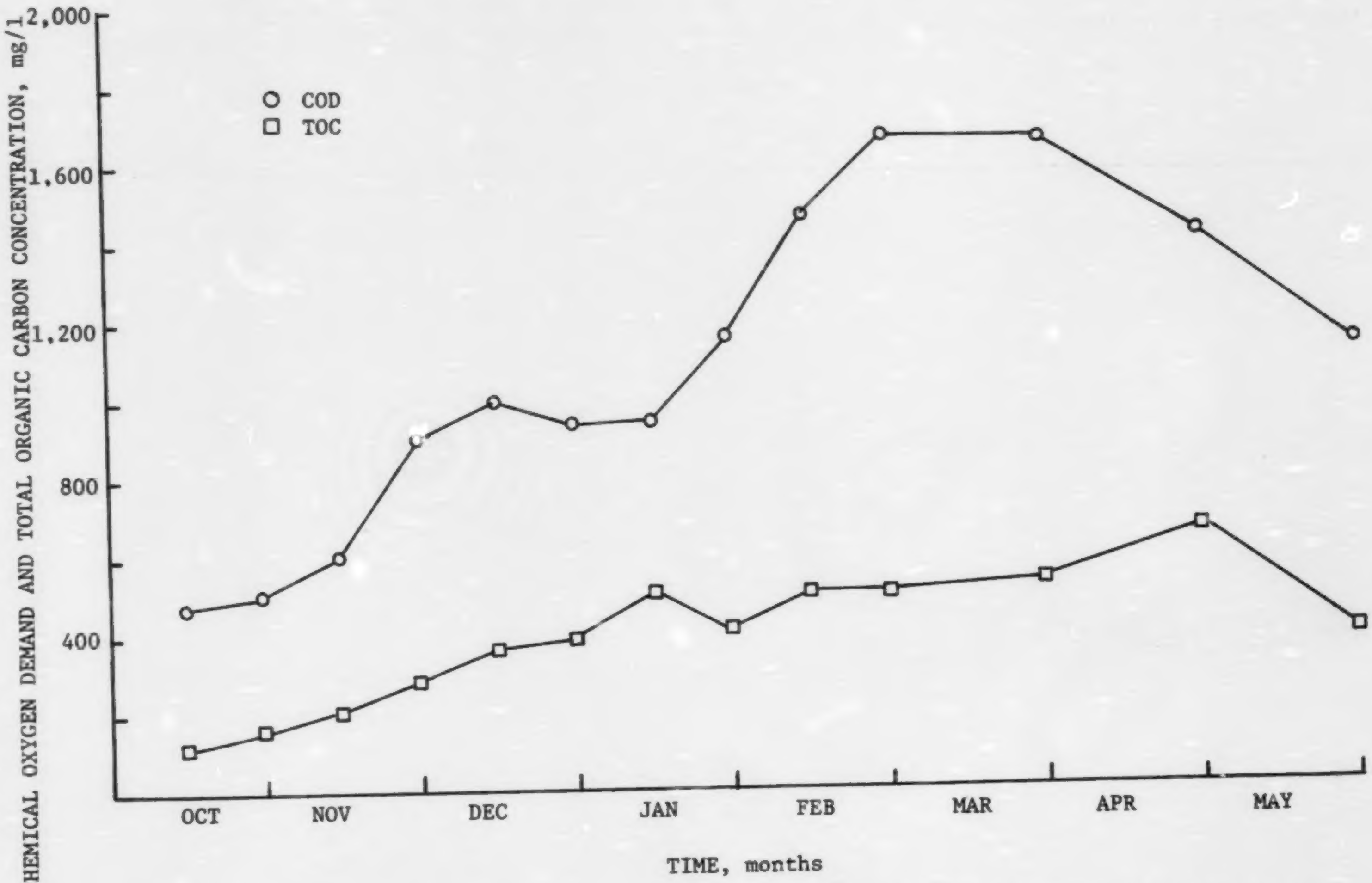


Figure 51. Supernatant COD and TOC concentration changes (two week averages) in field pilot scale lagoons loaded once per week at 0.25 times the reference rate for swine wastes.

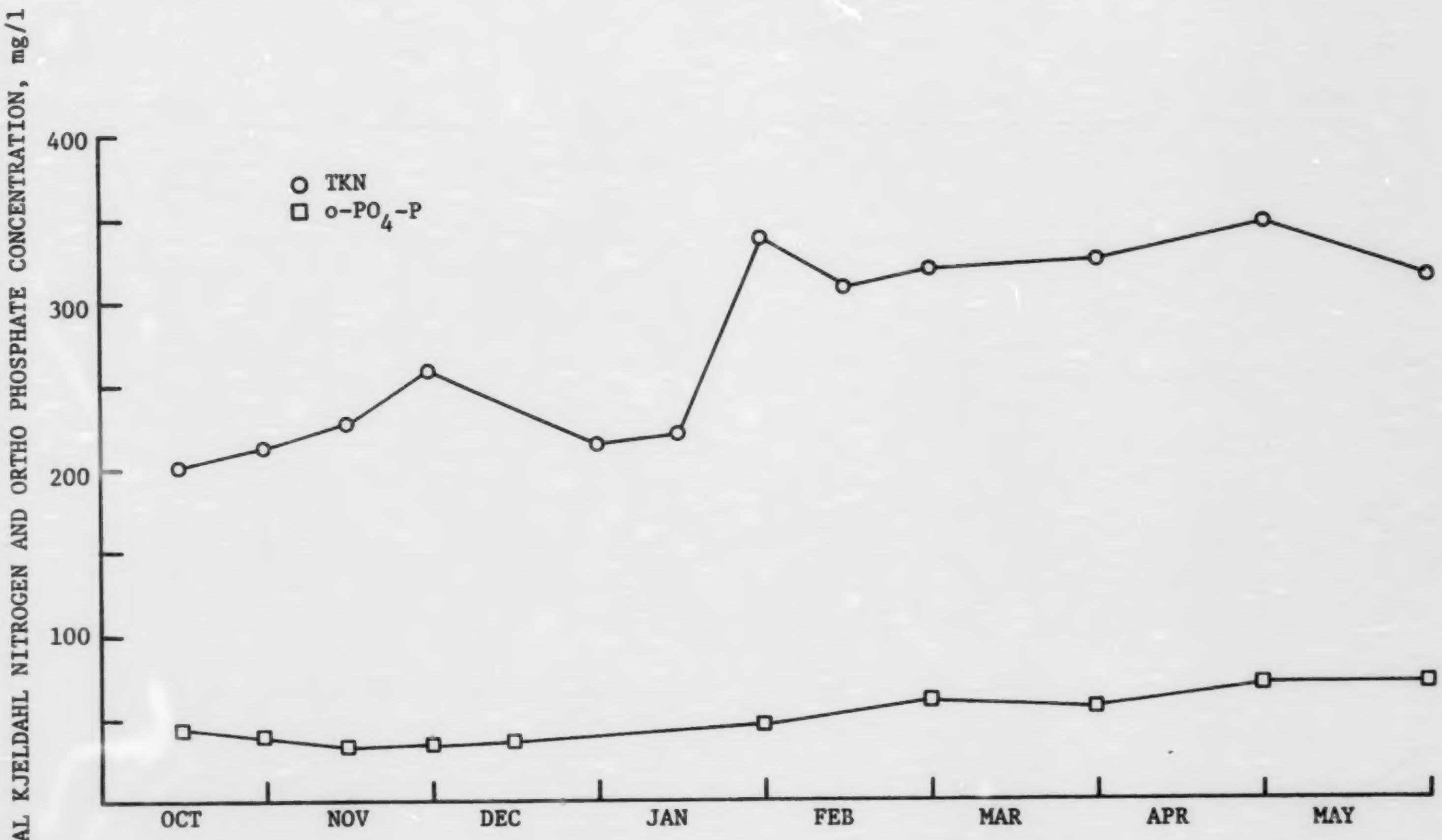


Figure 52. Supernatant TKN and o-PO_4-P concentration changes (two week averages) in field pilot scale lagoons loaded once per week at 0.25 times the reference rate for swine wastes.

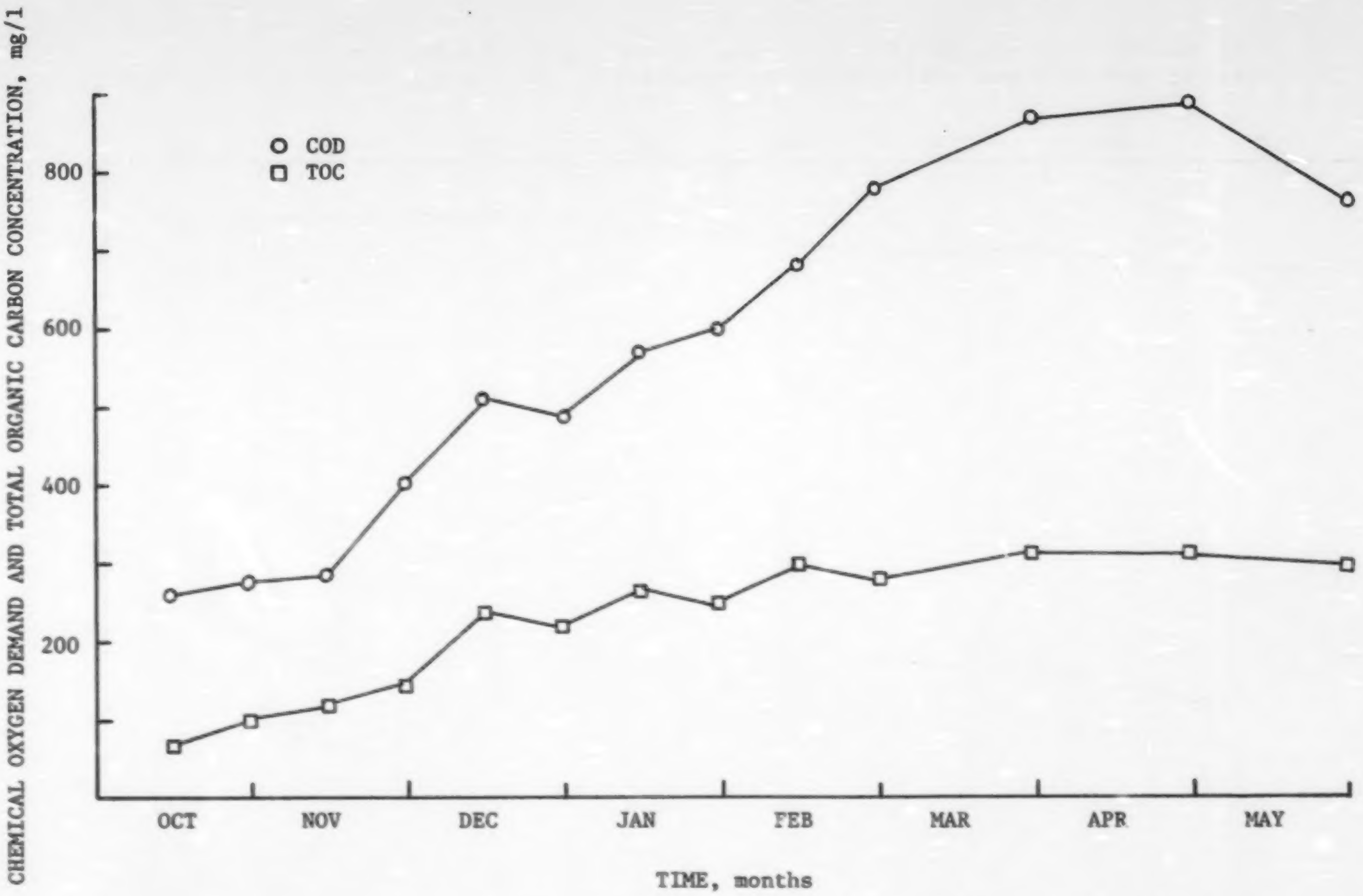


Figure 53. Supernatant COD and TOC concentration changes (two week averages) in field pilot scale lagoons loaded once per week at 0.125 times the reference rate for swine wastes.

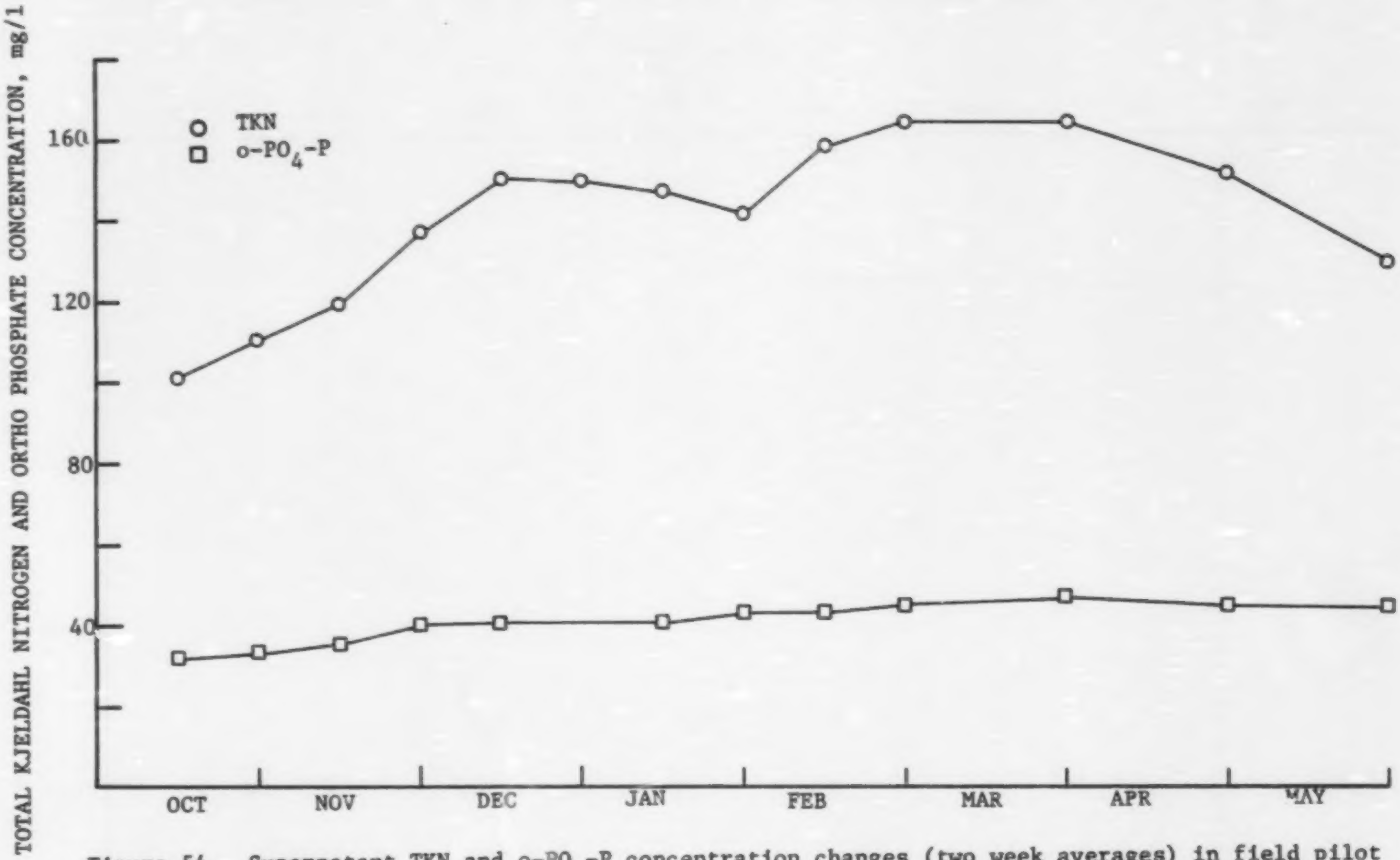


Figure 54. Supernatant TKN and o-PO_4-P concentration changes (two week averages) in field pilot scale lagoons loaded once per week at 0.125 times the reference rate for swine wastes.

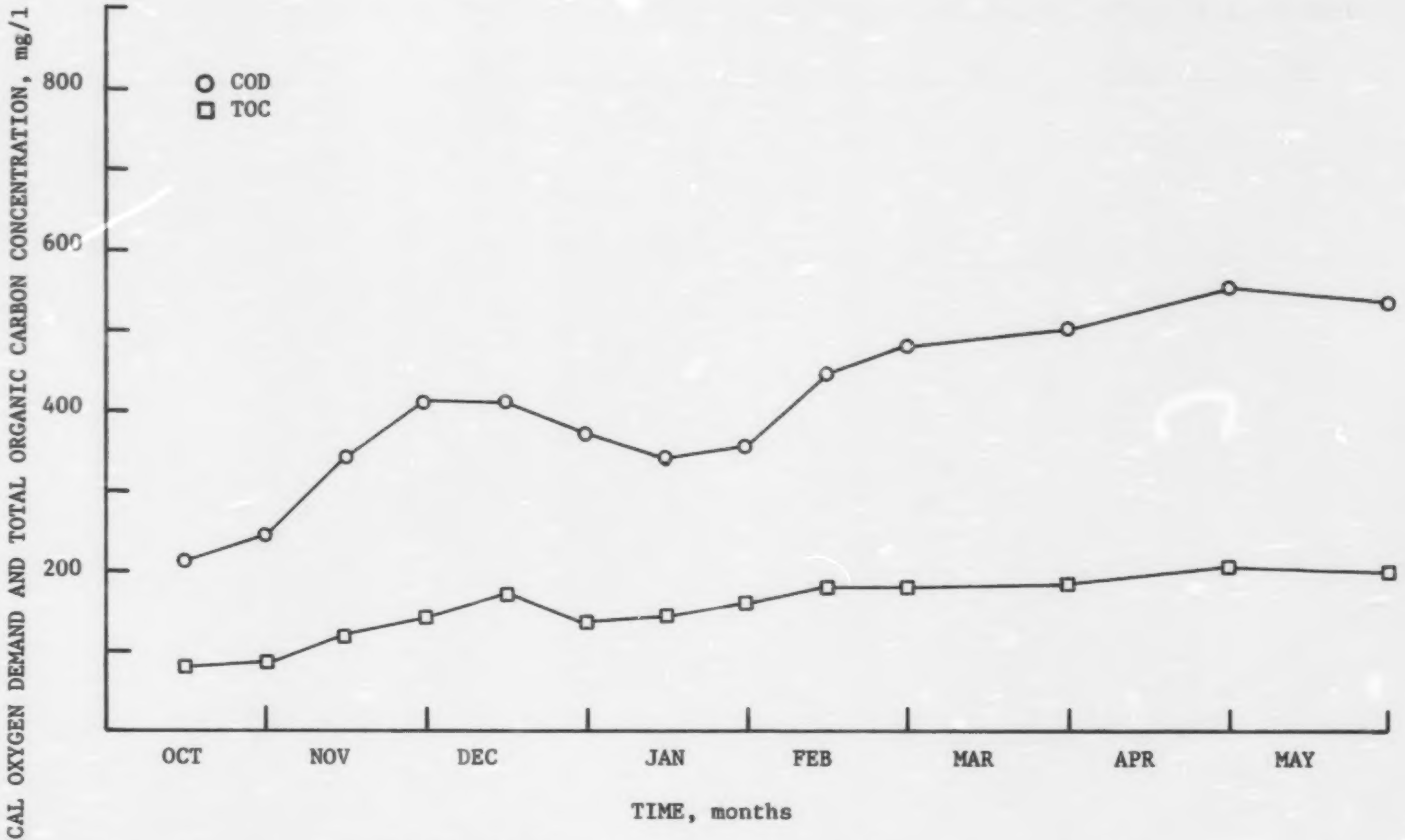


Figure 55. Supernatant COD and TOC concentration changes (two week averages) in field pilot scale lagoons loaded once per week at 0.0625 times the reference rate for swine wastes.

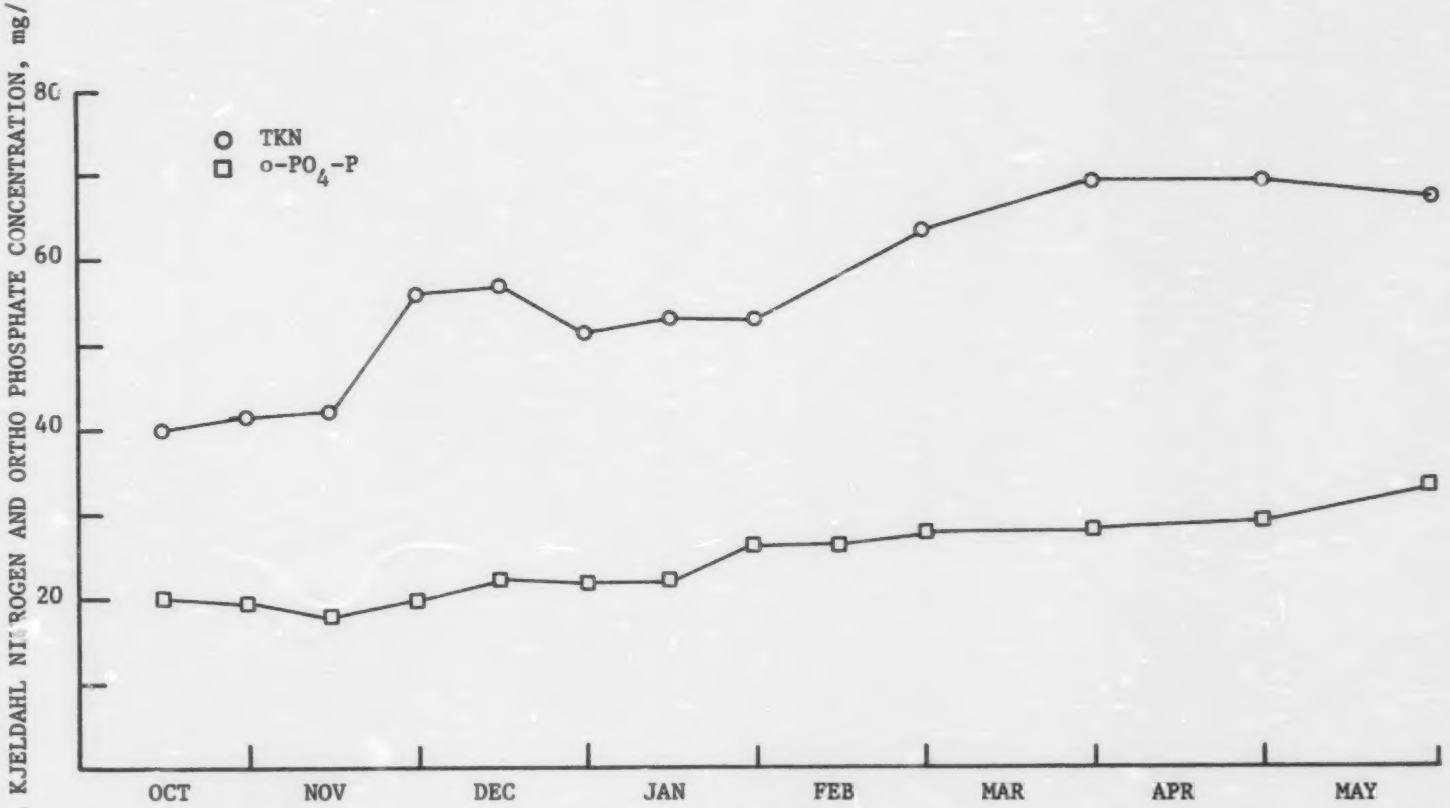


Figure 56. Supernatant TKN and o-PO_4-P concentration changes (two week averages) in field pilot scale lagoons loaded once per week at 0.0625 times the reference rate for swine wastes.

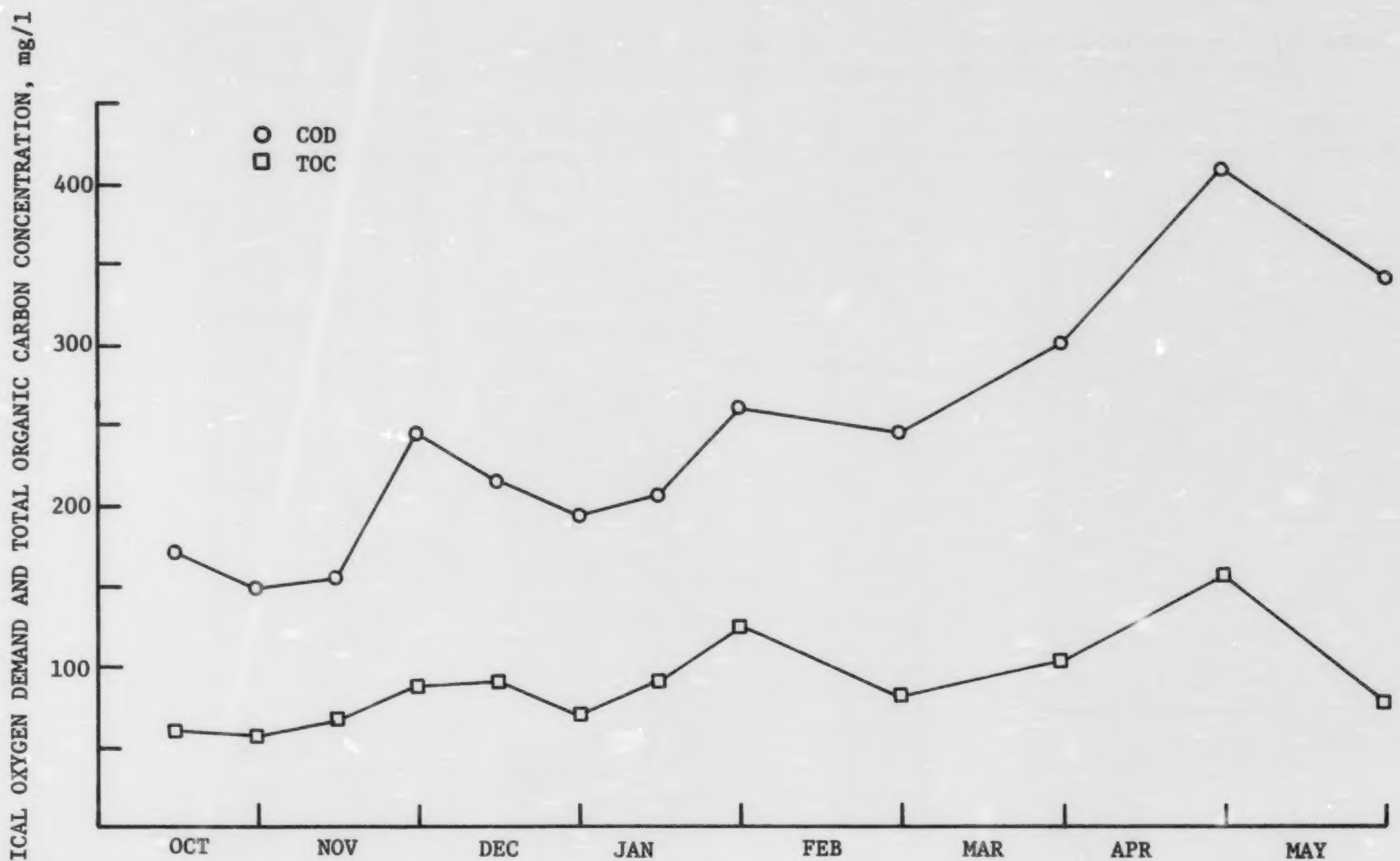


Figure 57. Supernatant COD and TOC concentration changes (two week averages) in field pilot-scale lagoons loaded once per week at 0.031 times the reference rate for swine waste.

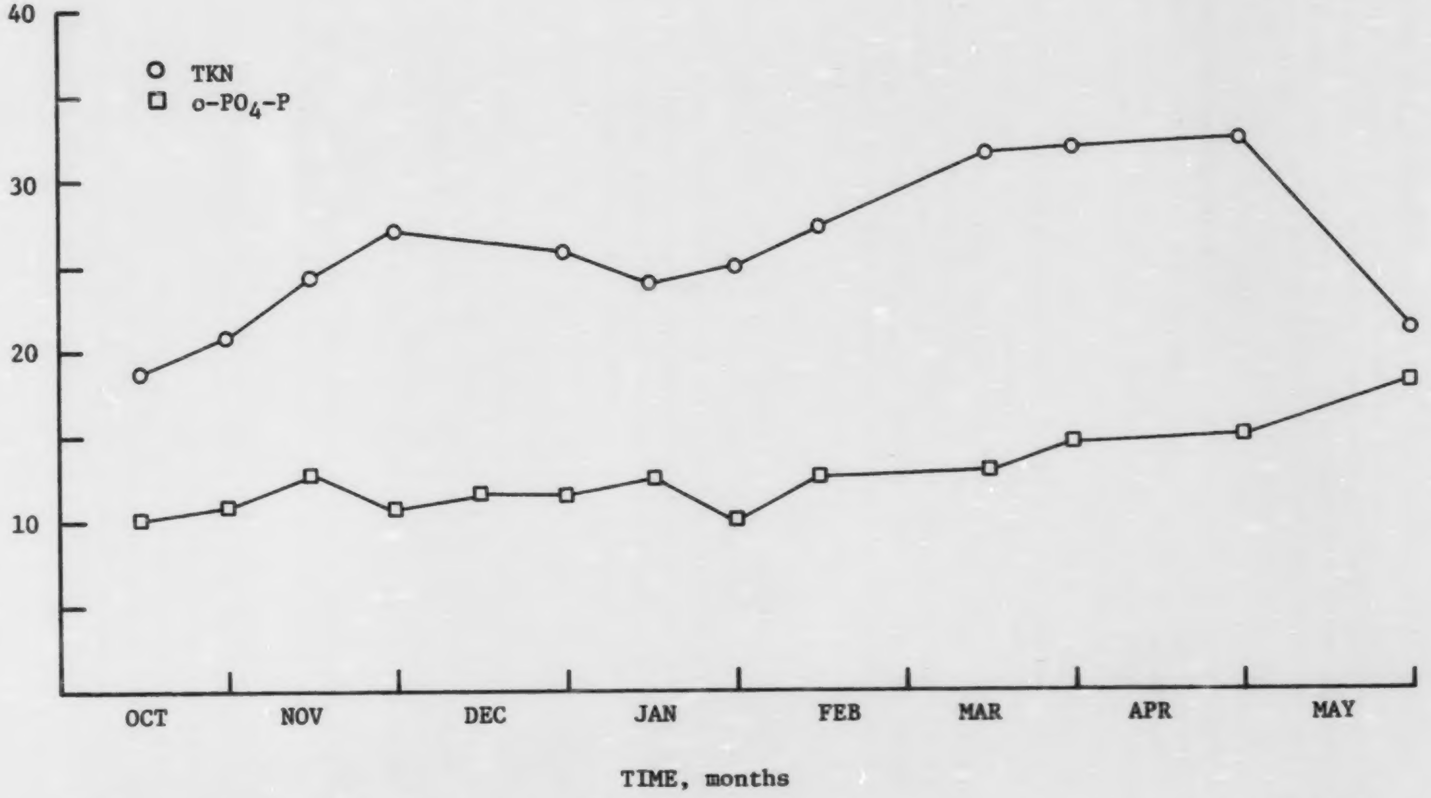


Figure 58. Supernatant TKN and o-PO$_4$-P concentration changes (two week averages) in field pilot scale lagoons loaded once per week at 0.031 times the reference rate for swine wastes.

pronounced in certain units, but in general by late April and early May, the four parameters monitored were close to a steady-state value. Shortly after this time, supernatant concentration values decreased with the warmer summer temperatures. Thus steady-state supernatant values derived from Figures 41-58 were for the winter-early spring period.

The temperature of the lagoon supernatant 1 meter below the surface was found to equal weekly average air temperature determined by averaging the daily maximum and minimum temperatures throughout a week period, Appendix B1. This temperature agreement continued throughout the annual cycle.

Temperature readings at the top (.15 m below surface) middle and bottom (within sludge blanket if present) were made on several occasions during the year, Appendix B1. For a given pilot-scale reactor temperature uniformity was within one to two degrees Celsius throughout the 1.8 m depth. The more heavily loaded unit evidenced a consistent one to three degree Celsuis higher temperature than the more lightly loaded units, particularly at the bottom. Heat of anaerobic microbial reactions or better solar heat entrapment may have been factors in the higher reactor temperature.

After the late winter to early spring period the supernatant concentrations began to decrease as the lagoon temperature began to increase. The responses of the various lagoons to the seasonal temperature change were quite different in that the time and rate of concentration decrease was not uniform or did not consistently seem to depend on loading rate. The explanation of seasonal lagoon supernatant changes is not presently available and these lagoons are being continued through an entire annual cycle.

Response and achievement of steady-state times were generally longest for TKN. COD was also less rapid than TOC in concentration response and was generally more variable as an indicator of supernatant quality while minimal response for ortho phosphorus was noted. These trends follow those noted in the laboratory units.

The steady supernatant levels of COD, TOC, TKN, and o-PO_4-P are listed in Table 22 for all loading rates investigated. The supernatant concentration of COD, TOC, TKN, and o-PO_4-P were found to decrease in value as the loading rate (kg COD/m^3/week) was decreased or as the lagoon volume (m^3/45-kg hog) increased. This trend was also similar to that observed with the laboratory units. However the steady-state concentration of the pilot-scale lagoons was considerably higher than laboratory units loaded at a comparable rate. Experimental reactor size and environmental factors could contribute to these differences.

Table 22. STEADY SUPERNATANT CONCENTRATION OF FIELD PILOT-SCALE LAGOONS LOADED AT VARIOUS RATES WITH SWINE WASTES

Loading rate (fraction or multiple of reference rate)	Concentration, mg/l			
	COD	TOC	TKN	o-PO_4-P
4	18,000	7,000	2,700	450
1 (first of series)	3,000	1,200	1,000	90
1A (second of series)	1,000	400	300	--
1B (third of series)	500	250	90	--
.5	2,100	700	600	75
.25	1,600	500	350	50
.125	900	300	150	50
.0625	500	190	70	25
.0312	250	90	30	15

The lagoon supernatant concentration for field pilot-scale lagoons was found to be homogeneous for the reference rate unit, Figure 59, and also for those units loaded at fractions of the reference rate. A sample taken at an intermediate depth thus was representative of lagoon supernatant, as also verified earlier for laboratory scale units.

The three lagoon units in series were originally connected directly by overflow pipes, Figure 39. In a recent EPA report[42] it was emphasized that short circuiting commonly occurred in lagoons when the inflow and outflow ports were not properly situated. With these small units, it was observed that during loading some of the input flowed directly into the next tank. Thus the connecting pipe between the first two units was sealed and excess supernatant was pumped with subsurface discharge each week from the first to the second unit. However, free flow between second and third lagoons was maintained. This more effectively compartmentalized the series system. However, supernatant quality data for the three lagoon system showed no noticeable effect due to management loading change. Thus, for this size unit no conclusive information regarding short circuiting was obtained. Additional supernatant concentration reductions did occur in the field pilot-scale series

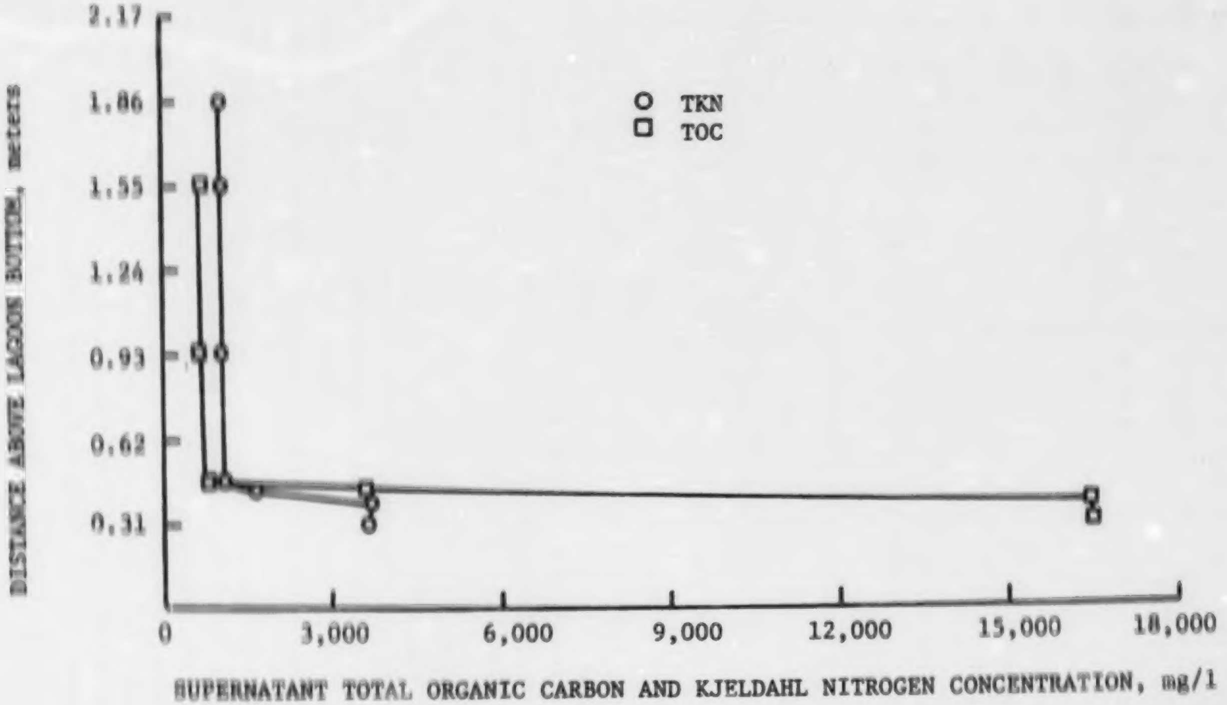


Figure 59. Liquid TOC and TKN concentration as a function of depth in an unaerated anaerobic, pilot-scale field lagoon loaded at the reference rate with swine waste.

reactors. At the steady-state conditions for the winter-spring period the effluent concentration of COD and TOC were approximately one-third and one-sixth of first lagoon levels for the second and third stage lagoons respectively. The TKN level for the second and third series units were one-third and one-tenth of the first lagoon effluent concentration. Thus, a somewhat greater percent nitrogen removal was recorded for the third unit compared with reduction of organics (COD and TOC).

Lagoon Surface and Physical Properties-

Among the field pilot-scale lagoons receiving different loading rates the unit receiving four times the reference rate had much different physical characteristics and correspondingly, chemical composition. Supernatant samples evidenced a characteristic thick fibrous slurry not found with lower loading rates. In addition the supernatant concentration of phosphate was quite high (450-500 mg/l o-PO_4-P). As discussed earlier in the laboratory cone experiments an upper limit of 50-80 mg/l o-PO_4-P according to a solubility limit appeared to exist for phosphate. The elevated phosphate level and supernatant composition observations indicated considerable hindered settling at this high loading rate. Samples were taken at several depths in the four times reference rate lagoon and waste parameter concentrations with depth are given in Table 23. The effects of the surface mat and the increase in concentrations with greater depths were evident. The other pilot-scale units did not evidence these concentration gradients with depth which further indicated hindered settling in the heaviest loaded unit. Because the supernatant concentration leveled off well below raw waste levels for this reactor, the increased levels of suspended material were in part offset by biological activity apparent from visual examination of gas bubble production and total bacteria assays.

Table 23. LIQUID CONCENTRATION AT SEVERAL DEPTHS FOR A FIELD PILOT-SCALE LAGOON LOADED WITH SWINE WASTES AT FOUR TIMES THE REFERENCE RATE

Distance above bottom (m)		Concentration, mg/l	
		Parameter	
	COD	TKN	o-PO_4-P
1.85 (surface)	11,000	3,500	420
0.92	6,000	1,900	230
0.62	49,000	4,600	2,500
0.31	67,000	5,400	3,900
0	73,000	5,800	6,800

Visual observations and physical evaluation of these pilot-scale reactors were made continuously as the experiment progressed. The surface of the most heavily loaded unit (4 times reference rate) had a pronounced scum layer which during hot periods was quite dry and mat-like. However, after loading and during periods of pronounced gaseous eruptions and sludge rising, the surface mat would break apart. The more lightly loaded lagoons (1, 1/2, and 1/4 times the reference rate) had a more liquid type of surface with variable scum amounts and location depending on wind or other conditions. The least heavily loaded units (1/8, 1/16, and 1/32 times the reference rate) had frequent algal blooms and thus a very different appearance; but when algal growth was not present, surface conditions were more like farm ponds than lagoons.

Field Pilot-Scale Lagoon Gas and Odor Generation-

The gas generation rate of the most heavily loaded unit was estimated by the time required to fill an inverted quart jar. The rate was about 210 liters of gas per m^2 of surface area per day or 113 liters per cubic meter of lagoon volume per day. For comparison, total gas production for high rate sewage digestors is about 4,000 liters per cubic meter of volume per day. The approximate concentration of lagoon gas was recorded to be about 70 percent methane and 25 percent carbon dioxide.

Odor from these lagoons varied considerably with climate conditions and loading rate. On many days with average humidity and wind conditions, offensive odor was not recorded for any of the units. However, on other days when odors were prevalent, a very rough judgment based on observations of researchers and students indicated that the unit loaded at 1/8 the reference loading rate was below the odor threshold. Individual consensus indicated that the frequency or probability of odor detection when visiting the site was 80 percent for the 4 times unit, 60 percent for the reference unit, 20 percent for the 1/2 unit, and little odor for units receiving 1/4, 1/8, or a lower fraction of the reference rate. For experimental reactors located in such close proximity as in this study, certainly odor interferences affect field evaluations.

In order to further relate odor threshold to loading rate, an odor panel approach was begun. Samples of lagoon supernatant, from the surface and from the one-meter depth were put in 200-ml wide mouth jars. A cover was placed on each jar and each panelist would remove the lid and waft the gases toward himself to rate the odor. The panel of 7 to 8 persons consisted of secretaries, faculty members, and laboratory personnel who were not heavy smokers. The rating scale was: 1 - strongly object, 2 - object, 3 - would not object, and 4 - not offensive. Colored samples of tap water were incorporated as a control. An odor rating sheet is presented in Appendix B2.

The odor ranking was the most offensive (1.14±0.56) for the surface of the unit receiving the heaviest loading rate and as loading decreased to the lowest rate, the odor ranking became less offensive (3.58±0.67), Table 24. The nature of the odor became questionable at the lower lagoon loading rates. Odor differences for all units between the surface sample and that from one meter below the surface were within one standard deviation and thus not significantly different which further indicated some homogeneity in lagoon supernatant.

The difficulty of an odor ranking system such as used here is that no odor characterization is included. Most natural water bodies and even some processed drinking water have an "odor" but generally typed as algal decay, mineral, sulfur, etc., rather than manure-related. Thus, the relative ranking by an odor panel was not an entirely valid indicator of an offensive or nuisance-causing lagoon loading rate. Further refinements of odor sensing and inclusion of field climatological conditions are necessary for the best characterization of the odor potential for different lagoon loading or design size.

Nevertheless, from the less refined aperiodic field observations and the results of the odor panel ranking the initial conclusion was that there was a discernible odor threshold at approximately 0.25 to 0.125 times the reference loading rate. Below this threshold, odor was not manure-like nor was an odor always detectable. Above 0.25 times the reference rate (9.3 m^3/45-kg hog) odor was not always detectable but when found it was characteristic of swine manure and hence, was deemed more offensive.

Table 24. DEPENDENCE OF PANEL-RATED ODOR RANK ON SAMPLING LOCATION AND LOADING RATE FOR FIELD PILOT-SCALE UNITS LOADED WITH SWINE WASTE

Lagoon loading (multiple or fraction of reference rate)	Sampling position (meters below surface)	Odor rank (Total scale: 4 - would not offend at all 1 - strongly object) Mean	Standard Deviation
4	0	1.14	0.56
4	1	1.34	0.52
1	0	1.47	0.79
1	1	1.39	1.04
0.5	0	2.00	0.70
0.5	1	1.63	0.87
0.25	0	1.85	0.60
0.25	1	1.98	0.77
0.125	0	2.67	0.68
0.125	1	2.44	0.81
0.062	0	3.29	0.71
0.062	1	2.74	0.82
0.031	0	3.58	0.67
0.031	1	3.17	0.82
Control		3.6	0.46

Lagoon Sludge-

After about 22 months of operation the sludge depth in these pilot-scale reactors was determined. The first technique used was a hollow tube, stoppered at the bottom, which was lowered to successive lagoon depths. At a given depth the stopper was removed and a sample taken. Another aliquot was taken at a lower depth until a number of depths were represented by samples. Then visual observations were made to determine the depth at which a consistency change was noted and this was termed the sludge depth. The results for this visual method of analysis for several lagoon loading rates are given in Table 25.

Table 25. SLUDGE DEPTH DETERMINATION FOR ANAEROBIC SWINE LAGOONS LOADED AT DIFFERENT RATES.

Unit loading rate (multiple or fraction of reference rate)	Sludge depth, m		
	Visual Method	Concentration change method	Sludge volume percent of input volume
4	--	0.77-0.92	9.5
1	0.33	0.44	16
0.5	0.28	0.36	12
0.25	0.21	0.14	24
0.125	--	0.13	

In order to further refine the visual technique for determining sludge depths, a number of samples were taken at several vertical positions with the hollow tube device, previously described and analyzed for TOC, o-PO_4-P, NH_3-N, and TKN (Appendix B3). A typical plot of these data, Figure 59, shows the sudden concentration increase marking the change from supernatant to sludge zone. The distance from the bottom to this concentration demarcation was noted as the sludge depth and these visual and chemical measurements for several lagoon loading rates are included in Table 25. The two methods for determining sludge depths gave similar results; hence, the simpler visual method was preferred, given the approximate nature of measuring techniques.

The sludge depths did not increase linearly with increased loading rates indicating that either compaction or biological activity reduced accumulation rate in swine lagoons. Sufficient numbers of samples from these field units have not been analyzed to determine the nature and factors affecting rate of sludge build up. Long-term sludge buildup was especially difficult to predict because of the variance in accumulation rates with the various laboratory, pilot-scale and field lagoon experiments. A the reference loading rate, which provided 2.3 m^3 of lagoon volume per 45-kg hog, the sludge buildup rate determined for the first two years of operation would result in lagoon filling after about 9 years. These pilot-scale field reactors have an impermeable bottom thus maximizing sludge buildup. Continued monitoring of sludge buildup for 5 to 10 years would be necessary to determine compaction and other sludge accumulation variables contributory to much slower lagoon filling noted in full scale units.

Lagoon Treatment Efficiency

The removal efficiency as defined earlier for the laboratory reactors was based on the influent and effluent concentrations and the assumption that the sludge accumulated at a slow rate. Calculated removal efficiencies for all units are summarized in Table 26. For the heaviest loading, 4 times the reference rate, removal efficiencies were quite low with organics being 40 to 50 percent, orthophosphorus being 25 percent, and no total nitrogen removal. These field unit removals were less than fifty percent as effective as the corresponding laboratory units. However, the relative efficiencies for the laboratory units were still the highest for carbon, medium for phosphate, and lowest for nitrogen.

The removal efficiencies improved with decreased loading rate so that at or below one-half the reference rate the organ carbon removal was 95+ percent. At one-eighth of the reference rate or less, the phosphate and nitrogen removals were 94+ percent. Thus, the conclusion, verified by laboratory results, is that a high removal efficiency for organic carbon (COD and TOC), nitrogen (TKN), and phosphorus ($o-PO_4-P$) was attained at realistic anaerobic swine lagoon loading rates. However, the quality of the lagoon effluent was still very poor and not suitable for stream discharge.

Miscellaneous Supernatant Quality Measurements

In addition to the conventional waste constituents used as performance measures of anaerobic swine lagoons, several other parameters were monitored on an occasional basis. Detectable levels of dissolved oxygen near the lagoon surface were not consistently found except for the 1/16 and 1/32 times the reference rate and the third series lagoon. Dissolved oxygen and supernatant COD and TOC data for these three field pilot-scale units included in Appendix B4 showed considerable variation although dissolved oxygen was consistently present. High levels of surface dissolved oxygen were found even when supernatant levels were as high as 600 mg COD/l (300 mg TOC/l). No dissolved oxygen was detected at the mid depth or bottom of any of the pilot-scale

Table 26. REMOVAL EFFICIENCIES (EQUATION 1) AND EFFLUENT CONCENTRATION OF VARIOUS PARAMETERS FROM PILOT-SCALE FIELD REACTORS LOADED WITH SWINE WASTE

Unit	Effluent COD, mg/1	Efficiency, %	Effluent TOC, mg/1	Efficiency, %	Effluent TKN, mg/1	Efficiency, %	Effluent o-PO_4-P	Efficiency, %
4	20,000	38	7,000	53	2,700	0	600	25
1	2,500	94	1,200	92	1,050	58	75	91
1/2	2,000	95	700	95	600	76	60	92
1/4	1,650	96	550	96	350	86	60	92
1/8	900	98	300	98	160	94	50	94
1/16	500	99+	175	99	70	97	30	96
1/32	250	99+	90	99+	32	99	15	98

Input concentrations:

COD - 40,000 mg/1
TOC - 15,000 mg/1
TKN - 2,500 mg/1
o-PO_4-P - 800 mg/1

units regardless of loading rate. Thus it was concluded that other factors beyond bulk supernatant concentrations controlled the presence or absence of surface dissolved oxygen. These phenomena were not fully developed.

The unit loaded at 1/32 of the reference rate was designed to be naturally aerobic based on Soil Conservation Service recommendations.[27] Loading and design recommendations for naturally aerobic lagoons are shown in Table 27, along with the operation criteria for the 1/16 and 1/32 unit. After the waste input was stabilized at 40,000 mg COD/1, no dissolved oxygen was found at depths greater than 10 cm below the surface in either the 1/16 or 1/32 times the reference rate units; hence referenced design criteria for unaerated aerobic lagoons for swine waste was not supported by this study. However, since effluent quality from even aerobic ponds is not sufficient to allow stream discharge the presence of bulk dissolved oxygen is relatively unimportant. Lagoons are only pretreatment units prior to land disposal; and since odor thresholds are at higher loading rates than specified for unaerated aerobic units, regulations or efforts to achieve aerobic ponds are counterproductive.

Table 27. DESIGN CONSIDERATIONS FOR NATURALLY AEROBIC LAGOONS AND PILOT-SCALE LAGOON PERFORMANCE

Source	Surface area, m^2 per 45-kg hog	kg BOD_5 per ha, per day
Soil Conservation Service	27.5	70 - 130
North Carolina	27.5	-
1/32 reference rate - pilot scale	41.2	37
1/16 reference rate - pilot scale	20.8	70

The second parameter monitored as a correlation to the chemical oxygen demand (COD) was the five-day biochemical oxygen demand (BOD_5). Results for COD and BOD_5 analysis on samples from the pilot-scale units during a steady operation period in May, 1974, are given in Table 28. The variability of the BOD_5-COD ratio further verified the many difficulties associated with the BOD_5 test.

Table 28. COMPARISON OF BIOCHEMICAL AND CHEMICAL OXYGEN DEMAND OF VARIOUS FIELD AND LABORATORY ANAEROBIC REACTORS LOADED WITH SWINE WASTE

Sample source	Multiple or fraction of reference loading	BOD_5 (mg/l)	COD (mg/l)	$\frac{BOD}{COD}$, %
Pilot reactors				
	4	4,600	21,500	21
	4	2,520	18,500	14
	1	386	2,000	19
	1/2	250	1,100	23
	1/4	460	825	56
	1/4	503	825	61
	1/8	210	625	34
	1/8	412	625	66
	1/16	95	550	17
	1/16	149	550	27
	1/32	54	200	27
	1A	190	900	21
	1A	110	900	12
	1B	22	475	5
Lab reactor				
1	1.2	113	1,515	8
1	1.2	693	1,570	44
2	1.2	104	1,439	7
2	1.2	223	1,439	16
3	1.2	117	1,511	8
3	1.2	269	1,515	18
4	1.2	98	1,476	7
4	1.2	240	1,476	16
Raw waste				
		3,800	6,718	57
		8,900	24,120	37

Because the dissolved oxygen level of the majority of the lagoons was zero, a more sensitive measure of anaerobic levels for the various loading rates was needed. The oxidation - reduction potential (E_h) has been used in anaerobic systems to measure the degree of reduced conditions. Converse[54] found that the E_h potential varied from +400 mV for aerobic systems to -250 mV for highly anaerobic conditions. Below a threshold E_h level of -50 mV to -100 mV odor was found to increase dramatically; hence Converse concluded that the presence of these lower, more reduced conditions was a good measure of the odor potential associated with anaerobic treatment of animal waste. Additionally, the odor associated with a waste system was more accurately evaluated by the oxidation-reduction potential (E_h) than the dissolved oxygen (D. O.) level.

It was attempted to use the laboratory approach of Converse to evaluate the odor threshold of these pilot-scale units. However, the oxidation-reduction potential of a given lagoon varied considerably over the 3-week data period, Table 29. Thus no opportunity existed for a reliable unit characterization by E_h potential. There was the expected trend toward more reduced conditions in the more heavily loaded units, but the week-to-week variability has so far limited the use of this parameter for lagoon studies.

The pH of the laboratory and field units were measured over a wide variety of temperature and loading conditions, Appendix B5. Lagoon supernatant was fairly constant ranging between 6.5 and 8.5 with the majority of the pH values between 7.3 and 7.8. The laboratory units were slightly more basic but no trend existed for changes in pH with loading rate or reactor concentration. The exception so far unexplained is that the second and third series lagoons characteristically had higher pH values than the other lagoons even though supernatant concentrations were similar to laboratory and field units at a fraction of the reference loading rate.

Pilot-Scale Aeration

The mixed culture microbial activity of a anaerobic lagoon breaks down the long-chain organic compounds characteristic of animal feeds and waste products to short-chain alcohols, amines, sulfide compounds, as well as other more stabilized gaseous products including methane and carbon dioxide. These short-chain molecules have characteristic odors which even at low levels are identified as nuisances. Observations of lagoons which have little or no odor indicate that the upper surface zone is aerobic or at least not highly anaerobic even though the lower zones are strictly anaerobic. Such lagoons have been termed facultative or diphasic and have little or no manure odor.

Table 29. OXIDATION-REDUCTION POTENTIAL MEASUREMENTS AT MID-DEPTH IN FIELD PILOT-SCALE ANAEROBIC SWINE LAGOONS

Lagoon loading (multiple or fraction of reference rate)	Date	Eh Reading
4	3/20	-340
1	3/20	-120
1A	3/20	11
1B	3/20	54
1/2	3/20	-22
1/4	3/20	-27
1/8	3/20	51
1/16	3/20	151
1/32	3/20	41
Raw waste	3/20	-232
4	3/23	-285
1	3/23	-183
1A (second series lagoon)	3/23	-105
1B (third series lagoon)	3/23	-110
1/2	3/23	-160
1/4	3/23	-208
1/8	3/23	-139
1/16	3/23	-135
1/32	3/23	-86
4	3/27	-290
1	3/27	-200
1A (second series lagoon)	3/27	-165
1B (third series lagoon)	3/27	-142
1/2	3/27	-186
1/4	3/27	-230
1/8	3/27	-200
1/16	3/27	-161
1/32	3/27	-106
Raw waste	3/27	-272

An engineered equivalent of these facultative lagoons is achieved by the use of a mechanical device for adding oxygen to the upper zone by promoting mixing and pumpage across the entire lagoon surface. These surface aerators of which there are a number of commercial types increase oxygen transfer by various mixing or surface agitation patterns. In order to test horsepower requirements, degree of stabilization of waste constituents, and level of odor control associated with surface aeration two additional pilot-scale units were installed at the swine research site, Figure 40. As with the other pilot-scale units, these were 2.5 meters deep and 3.5 meters in diameter. Metal bottoms were fabricated to prevent any seepage. A catwalk superstructure spanning the tank diameter at the top of the lagoon was constructed to support a fixed aerator, Figure 60. The fixed aerator was chosen because of the small horsepower requirements for this pilot-scale volume (maximum 250 watts). A 187 watt, variable speed, mixer-aerator was selected. The impeller was specified to be just completely submerged below the liquid surface. The constant liquid level required to maintain proper impeller submergence was achieved with an overflow stand-pipe and a water reservoir controlled by a mechanical float valve to counterbalance rainfall and evaporation, Figure 60.

The first field pilot-scale unit was operated at an impeller rotational speed of 65 rpm while the second unit aerator speed was 110 rpm. These speeds required 37 and 60 watts, respectively. Each reactor was charged with two times the reference loading rate at a once-per-week frequency resulting in 840 liters per week of raw swine waste at a constant concentration 40,000 mg COD/1. The operation and sampling were the same as the field pilot-scale unaerated anaerobic lagoons.

Phase One Experiment-

The surface aeration experiments were divided into two phases with the first beginning after the swine waste input was held constant at 40,000 mg COD/1 (October, 1973). For the first experimental phase (power input 37 and 60 watts, respectively), the supernatant concentrations averaged over two-week periods are presented in Figures 61 - 64. Steady-state concentrations for COD, TOC, and o-PO4-P were achieved more quickly than for TKN, 20 weeks versus 25 weeks from initiation of uniform waste input. The relative rate steady condition attainment among the various parameters was the same as that observed for unaerated anaerobic units, both field pilot-scale and laboratory reactors. Steady conditions were reached at about the same time for both aeration rates indicating temperature, chemical transfer or microbial reactions were as important in governing supernatant concentrations as oxygen transfer or mixing intensity.

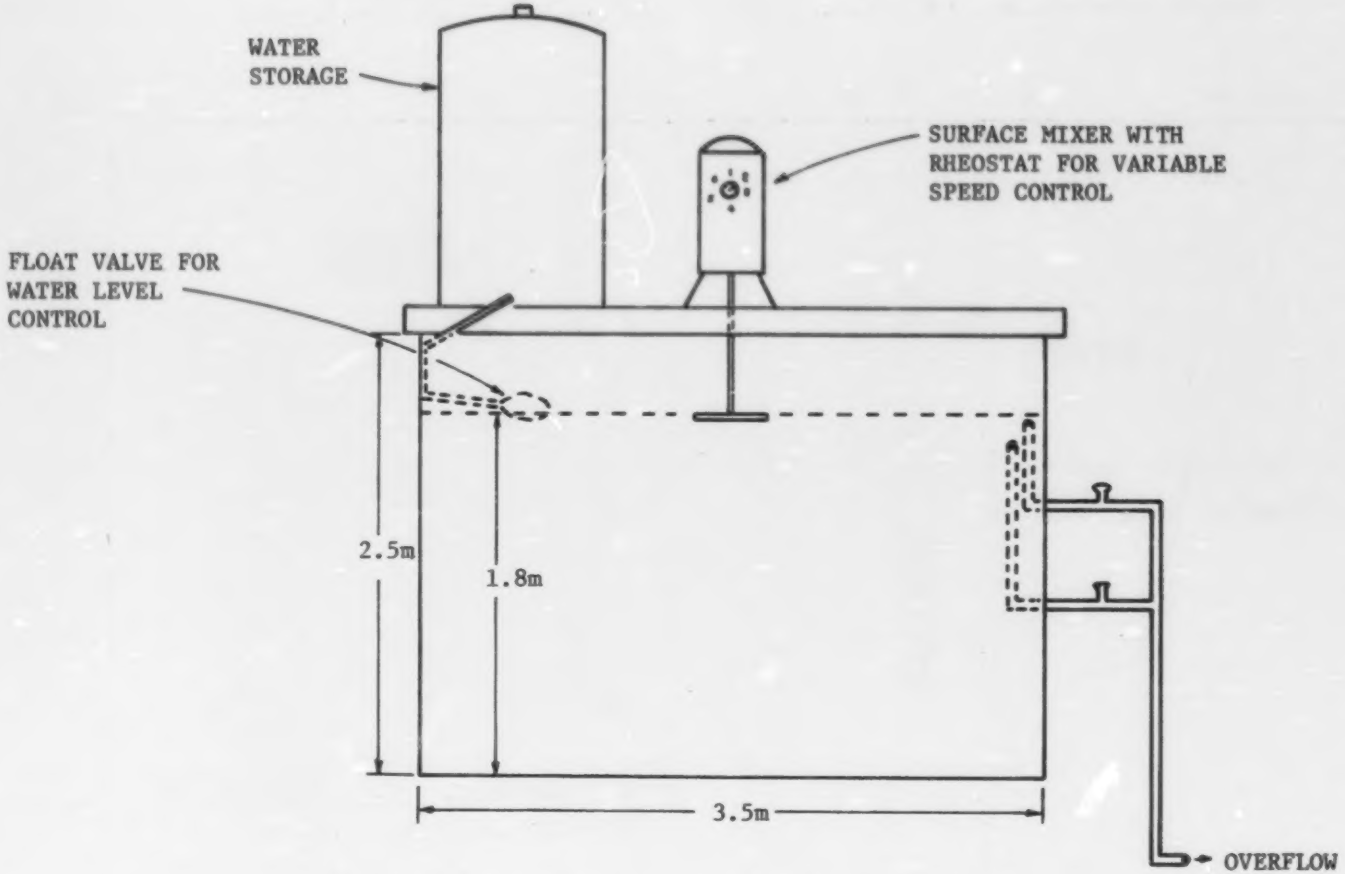

WATER
STORAGE
SURFACE MIXER WITH
RHEOSTAT FOR VARIABLE
SPEED CONTROL
FLOAT VALVE FOR
WATER LEVEL
CONTROL
2.5m
1.8m
3.5m
OVERFLOW

Figure 60. Schematic or aerated pilot-scale lagoon with water level control for fixed surface aerator.

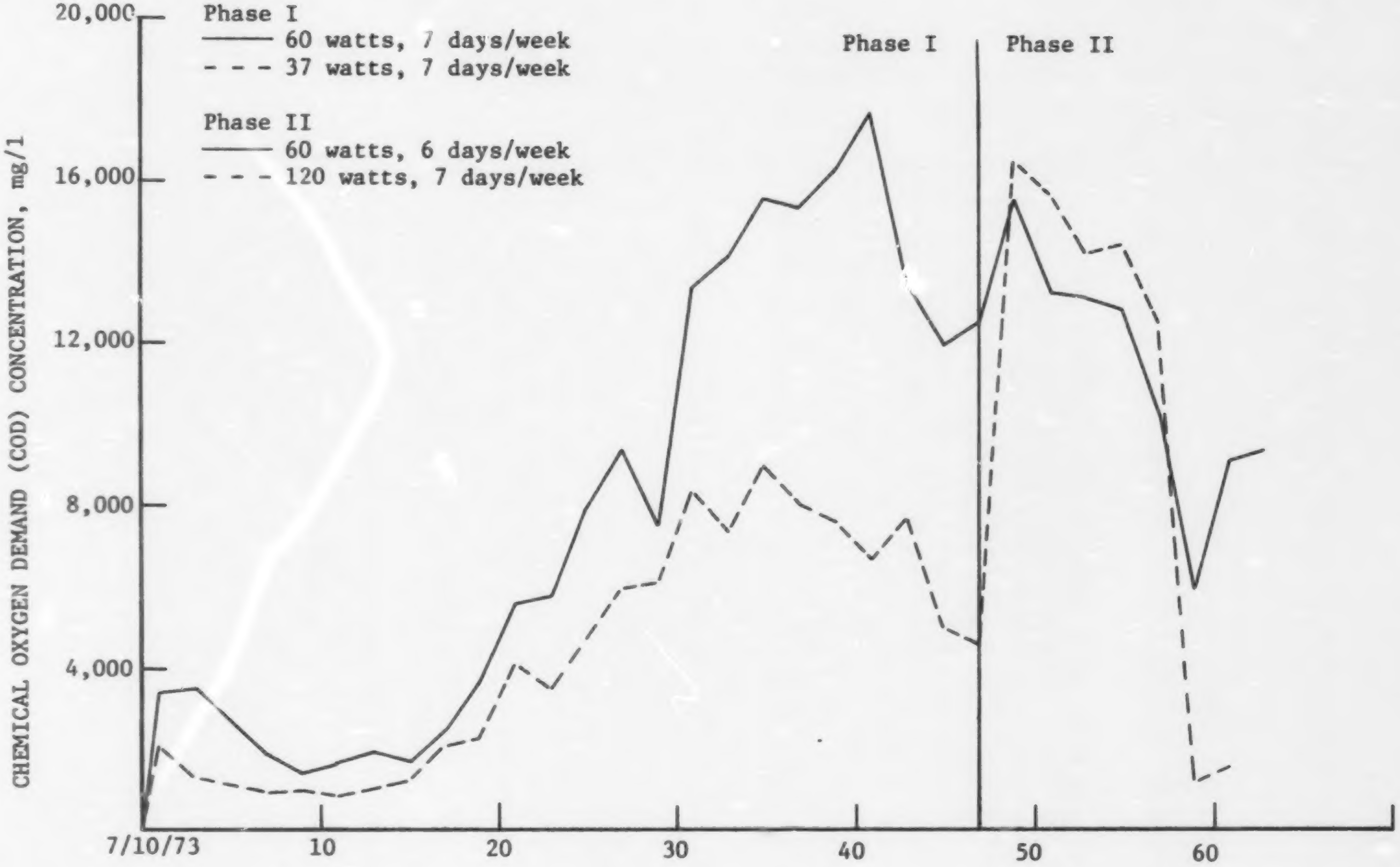


Figure 61. Supernatant COD concentration for field pilot-scale lagoons with surface aeration loaded once per week at 2 times the reference rate for swine wastes.

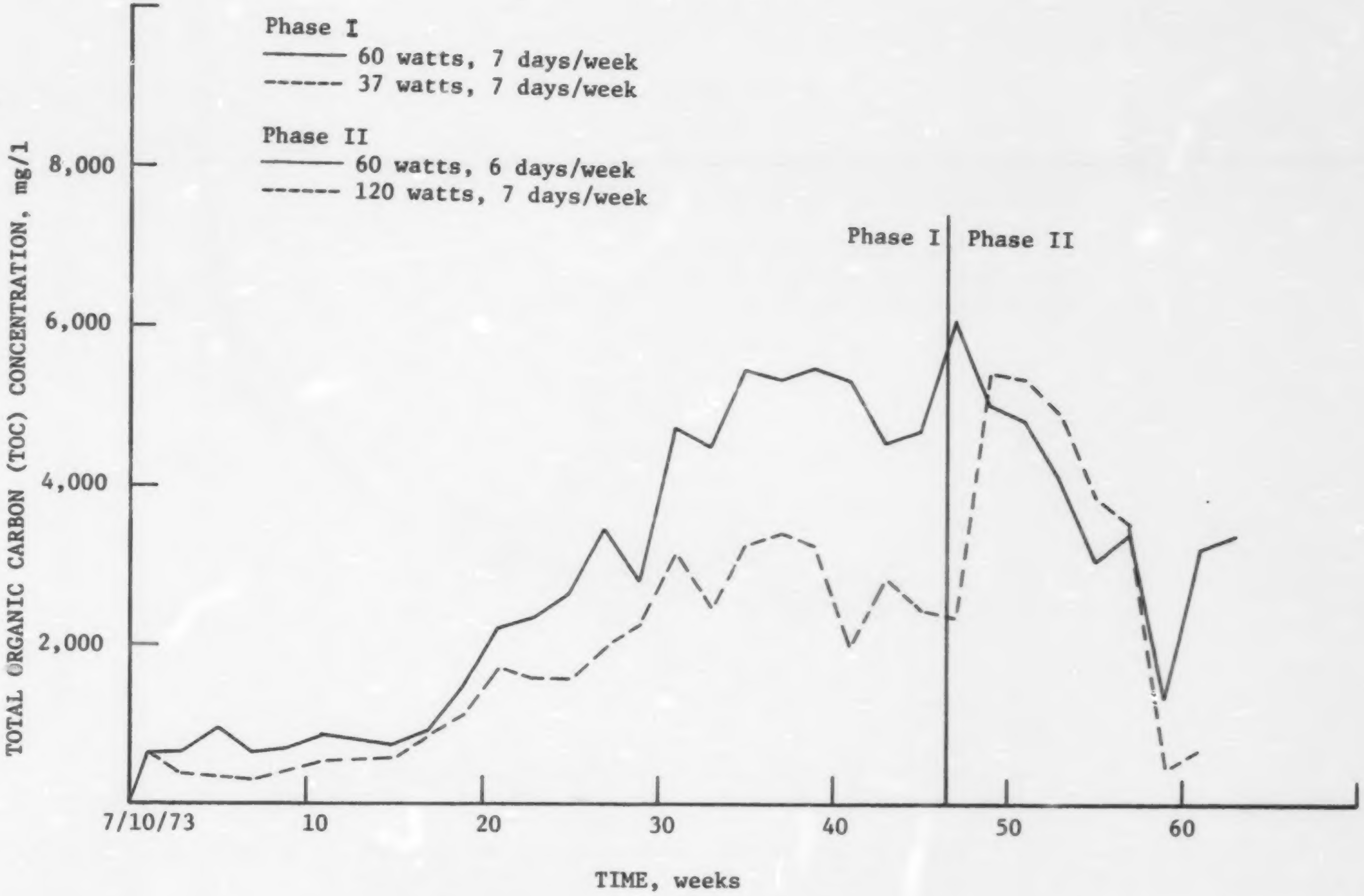


Figure 62. Supernatant TOC concentration for field pilot-scale lagoons with surface aeration loaded once per week at 2 times the reference rate for swine wastes.

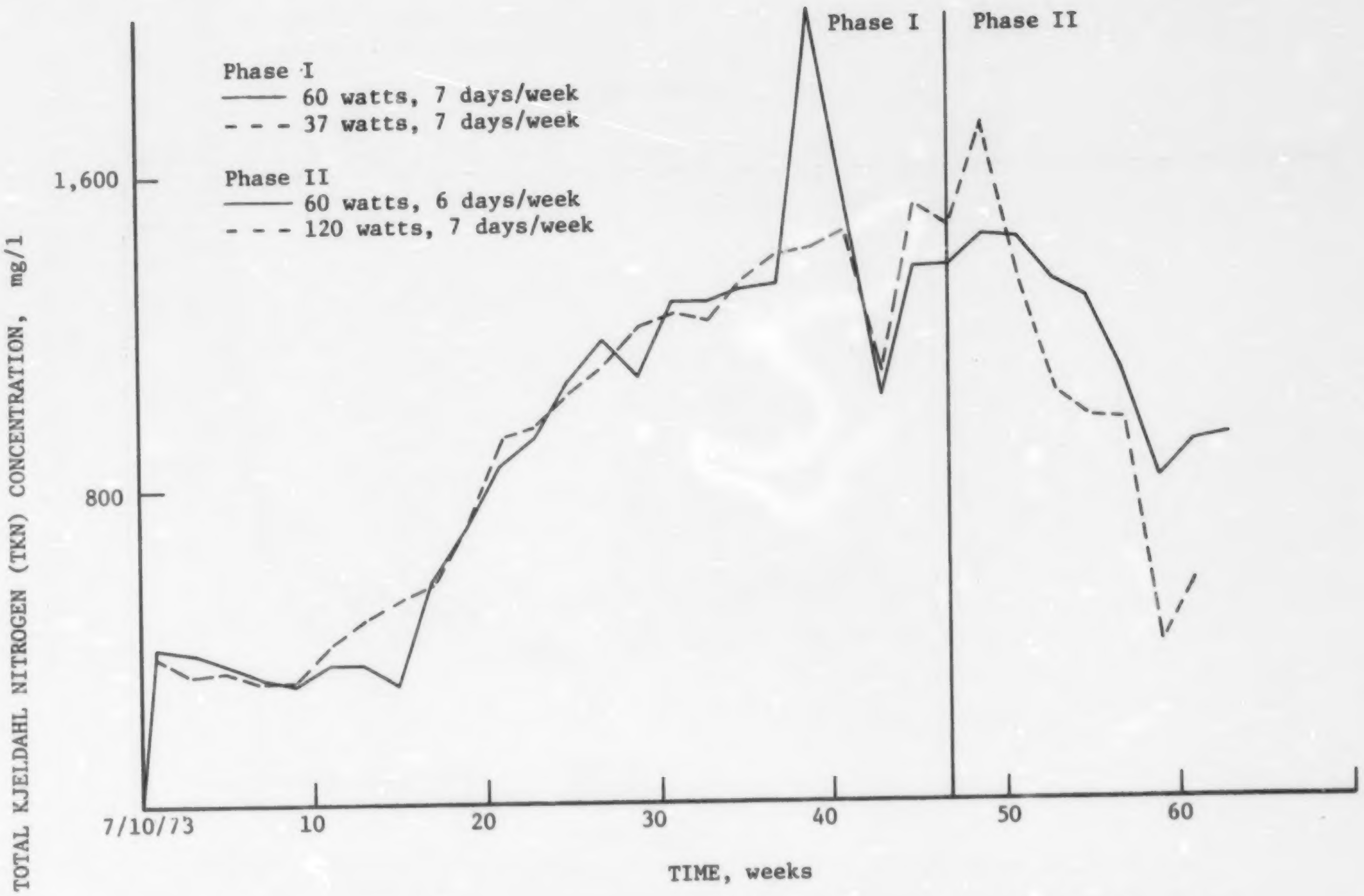


Figure 63. Supernatant TKN concentration for field pilot-scale lagoons with surface aeration loaded once per week at 2 times the reference rate for swine wastes.

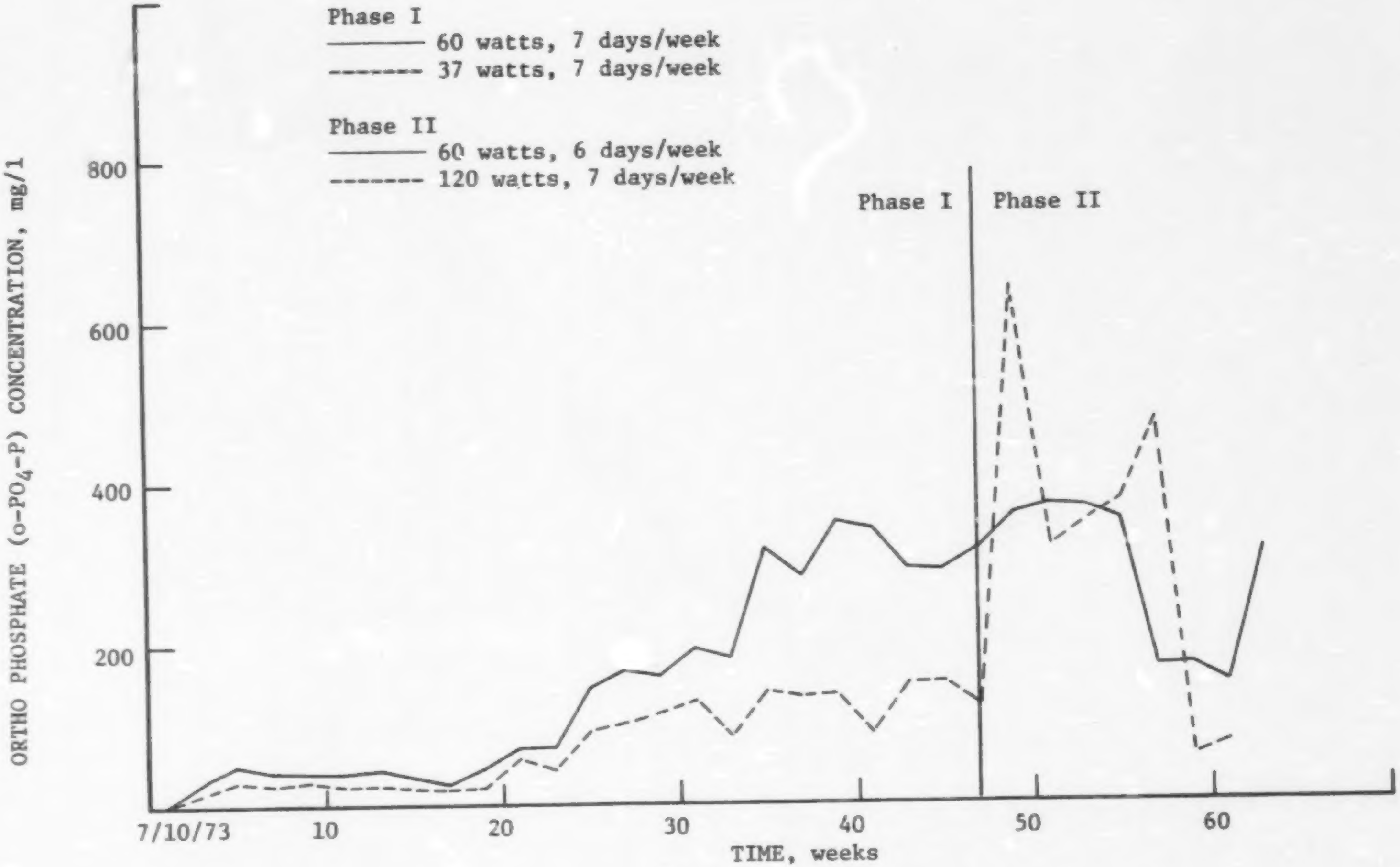


Figure 64. Supernatant o-PO$_4$-P concentration for field pilot-scale lagoons with surface aeration loaded once per week at 2 times the reference rate for swine wastes.

The final supernatant concentration in these surface aerated units was affected by a complex combination of particulate settling, surface agitation and evaporation, and aerobic and anaerobic reactions. Overall, the supernatant concentration of these units loaded at two times the reference rate was greater than pilot scale units discussed earlier loaded at the reference rate and was usually less than the anaerobic unit loaded at four times the reference rate. Thus, on a very rough basis the supernatant concentration appeared to depend on the swine waste loading rate in a manner consistent with other unaerated anaerobic units, although there were a number of conflicting factors.

The _a priori_ predicted levels of organics in aerated systems are dependent on input waste concentration (COD), reactor volume, and aerator horsepower. For a given waste type, continuous aerator operation, and a fixed reactor size, the greater the horsepower the greater the oxygen transferred and hence the more organic stabilization and lower COD expected. Manufacturers estimated oxygen transfer rate for most surface aerators is about 2 kg oxygen per hour per kilowatt. Calculations based on the COD load (2 times reference rate) and the manufacturer's oxygen transfer rate for continuous operation indicated that the unit with the higher aeration input received about 70 percent of the oxygen needed for complete stabilization and the lower one about 40 percent. Subsequently, an approximate oxygen balance to verify the manufacturer's oxygen transfer rate was performed during the second phase of experimentation. Thus, the pilot-scale reactor with the higher power setting was anticipated to have a lower COD supernatant concentration because of greater oxygen transfer. However, it was found that the higher aerated unit had greater COD, TOC, and orthophosphate concentrations but about the same Kjeldahl nitrogen level as the lower aerated unit, Figure 61-64. To explore reasons for this concentration trend, procedures were initiated to more completely evaluate the employed surface aeration.

The degree of mixing was first determined at a number of aerator speeds with a OTT-Current Meter which measured the fluid velocity and direction and thus could be used to determine the depth of aerator influence or significant flow patterns. From this method it was found that at the surface for 37 watt power input the fluid velocity decreased from 20 cm/sec at 15 cm from the impeller to 6.4 cm/sec at 45 cm from the wall. For the 60-watt setting these spatial velocities decreased from 25 to 11 cm/sec over the same distances from the aerator. Fluid velocities below the surface should be detectable to the lower limits of the current meter (0.025 m/sec). However, it was found that the mixing zone could not be adequately defined by this current meter approach; therefore, samples were taken to determine the variation of parameter concentrations with depth in both aerated units.

The orthophosphate concentration at several depths for the high and low aeration rate units are given in Figure 65. Both units had the same raw waste input, loading frequency, and management but different power inputs. Depth profiles showed a uniform upper zone and then an abrupt concentration increase, indicative of the sludge blanket. However, for the high aeration unit, the sludge depth was less and supernatant phosphate concentration was higher (by a factor of three, 350 versus 125 mg/l) than for the low aeration unit. This resulted from the greater resuspension of sludge and hindered settling associated with the greater aeration rate. Both aerated units had supernatant concentrations above the levels of 40 - 80 mg/l phosphate found in the unaerated field pilot scale units. These facts indicated that the depth of aerator influence was greatest for the 60 watt aerator settling (1.7 m) and that this mixing caused an abnormally high supernatant concentration despite the greater oxygen input obtained at this aerator setting. The lower aeration reactor (37 watt) had a smaller mixing zone depth of 1.4 m. It should be noted that the field pilot unaerated units also had uniform supernatant concentrations. However, because of the higher levels of orthophosphate, it was concluded that the uniform supernatant was evidence of aerator agitation and not the inherent homogenity phenomena associated with comparable unaerated units.

This investigation thus suggested that the higher organic levels were due to the increased agitation and thus suspension of sludge solids. Because the phosphate level was about three times greater at the higher aeration rate, Figure 64, and the organic level (COD and TOC) for this unit was only twice as high, Figures 61 and 62, the expected higher level of oxygen addition and organic stabilization for the greater horsepower input was realized. There were no distinct aerobic zones at either aeration rate and no dissolved oxygen was found even in the surface layer of these lagoons.

The supernatant ammonia concentration was 1,250-1,300 mg/l at 60-watt power input and 900-950 mg/l at the 37-watt level. Thus there was only about 40-50 percent difference in ammonia between these units. The supernatant TKN levels in the reactors were about 1500 mg/l for both aeration rates. Compared to phosphate or COD, the nitrogen concentrations were more similar between units showing that the greatest impact of aeration was on ammonia volatilization. Because ammonia loss is gas phase limited,[82] the augmentation in gas phase turbulence and the increased surface renewal of reactor liquid due to aeration increased ammonia volatilization potential. Thus, the expected resuspension of sludge at higher aeration input was counteracted partially by increased volatilization.

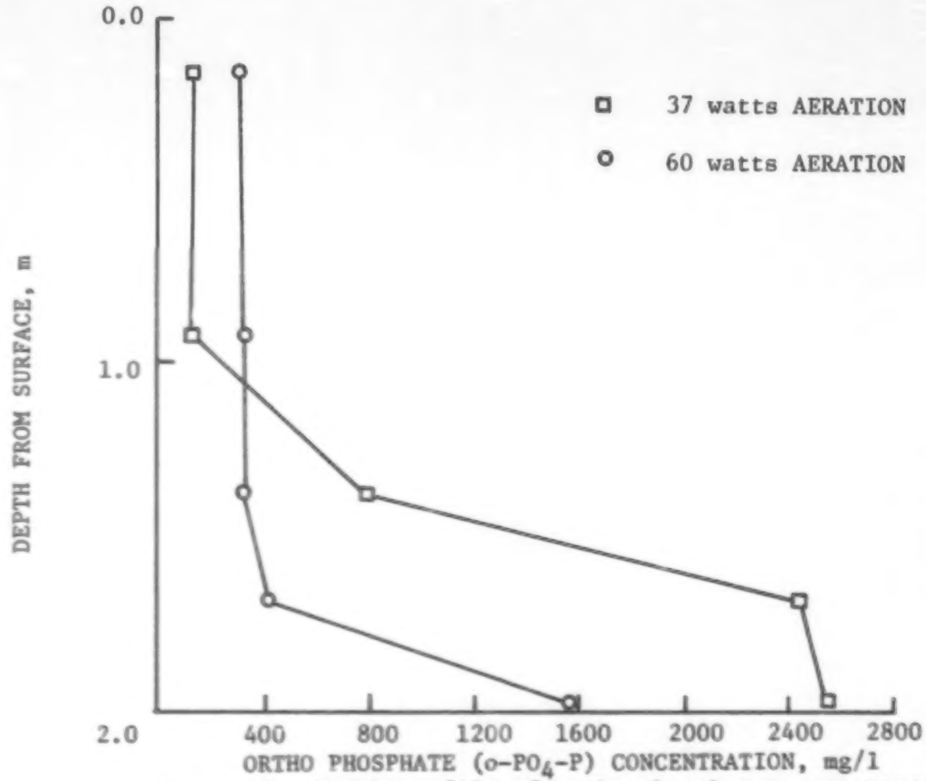


Figure 65. Depth profile of ortho phosphorus concentration for pilot scale swine lagoons receiving different rates of surface aeration.

Gas and Odor Generation-

Observations regarding odor were made on a number of different occasions after these pilot-scale units were being operated at steady-state conditions. These observations were by no means rigorous but on the average the more intensively aerated unit had less (sometimes even no odor) than did the lightly aerated unit. The higher horsepower input caused the liquid to be thrown into the air in droplets while the lower horsepower input only disturbed the liquid in a wave-like manner. The relative effects of oxygenation, volatilization, and surface mixing due to the employed surface aerator are not exactly known; hence, a complete qualitative and quantitative explanation of mechanisms for odor control has not been developed. The power in terms of watts/m^3 of volume were 3.3 and 2.1 for the two reactors. The required power input per unit volume to achieve a consistent, high level of odor control depends on the lagoon depth and shape as well as a number of other factors that could not be specifically determined from this field pilot-scale study.

When the aerator in either reactor was stopped, a large number of bubbles were observed to evolve from the liquid surface. The investigation of this phenomenon covered two different premises. The first was that in the surface layer there was a population of microorganisms which nitrified the ammonia present, and as the liquid was drawn into the lower zones containing anaerobic microorganisms denitrification occurred. The liberated nitrogen was then released as bubbles. The second premise assumed that entrapped air lost oxygen content as it passed through the anaerobic liquid and then the remaining gas which would be primarily nitrogen was liberated in surface bubbles.

Gas samples were taken from these reactors at the surface and analyzed for various gases, Table 30. There was considerable variability but significant levels of nitrogen were present as well as oxygen. The presence of methane indicated anaerobic activity but the nitrogen source or conversions could not be inferred from these data since both premises allowed nitrogen as a constituent of the bubbles formed. The bubbling observed after the aeration was stopped appeared to be sustained although the exact duration was not measured. However, because of the surface disturbances during aeration, it could not be determined if the bubbles were liberated continually. Nitrate analysis of this high COD supernatant was difficult because of analytical interferences and the potential for denitrification. Taking these factors into consideration, the nitrate level in both aerated reactors was in the range of 0 to 15 mg NO_3-N/1. This was low compared to oxidation ditch levels but does not rule out the generation of significant amounts of nitrates. That is, if nitrification and denitrification were occurring simultaneously, the nitrate level might in fact remain low while significant steady-state nitrogen losses occurred. Unfortunately, with these aerated field reactors, a mass balance on nitrogen would not indicate nitrification-denitrification losses because of the confounding effect of ammonia volatilization. Hence, further supportive experiments are needed to refine these initial aeration results and proposed mechanisms.

Table 30. GAS COMPOSITION FROM FIELD PILOT UNITS RECEIVING DIFFERENT AERATION INTENSITY

Date	Aeration, watts	Parameter volume percentage			
		O_2	N_2	CH_4	CO_2
7/16/73	60	2.6	30.2	67.2	trace
7/19/73	60	2.0	35.6	61.0	1.4
8/1/73	37	4.0	91	4.0	1.0
7/2/74	120	2.0	96	0.0	2.0
7/11/74	120	4.0	76	18	2.0

Phase II Experiment-

After 5 to 10 weeks of operation at the steady-state supernatant concentrations attained in phase I, the management of these two reactors was changed as phase II of these experiments. It had been concluded that both units had hindered settling or enhanced sludge suspension. The management of the high aeration reactor was changed so that after raw waste loading the aerator was stopped for 24 hours. This time period had been shown to be more than adequate for solids settling[80] so that any aerator effect which hindered initial settling would be overcome. After 24 hours the aerator was restarted. The expected result would be lower supernatant concentrations due to enhanced settling. The other reactor initially at the lower power setting was increased to 137 rpm or 120 watts to determine the impact of greater aeration input. Both units remained at the same swine waste loading rate and frequency.

The supernatant concentration changes for these new management variables are shown in Figures 61-64. As expected, concentrations for the reactor with the power change from 37 to 120 watts immediately increased above those for the 60-watt unit, due to the deeper mixing zone and thus greater bottom sludge scour. Unexpectedly, TKN showed only a modest increase. A possible explanation is that the increased volatilization compensated for the greater part of the expected concentration increase.

That ammonia volatilization was greater for increased aeration levels was indicated by the lower supernatant TKN concentration for the 120-watt versus 60-watt unit (after the 52nd week), Figure 63.

The decline of COD, TOC, and TKN in both aerated units after the 52nd week (July 15, 1974) roughly followed that of unaerated units and was due to greater biological activity and volatilization at warmer liquid temperatures. Because of this warmer temperature interference, direct quantitative comparison of the various management schemes was not possible. Qualitatively, the 120 watt input did not proportionally increase the COD, TOC, TKN, or o-PO_4-P concentrations as would be indicated by concentration changes between the 60 and 120 watt operation after initial concentration increased due to bottom scour. The decline in orthophosphate values (56-61 weeks) was not explainable although the unaerated pilot-scale lagoon loaded at 4 times the reference rate behaved similarly. If the supernatant phosphate removal mechanism is a precipitation, this would not be improved at higher temperatures on a solubility basis. The heavily loaded unaerated unit was found also to have hindered settling; thus, it may be possible that the decline in phosphate concentration was associated with improved settling characteristics with higher liquid temperatures. The complete explanation is not yet clear.

Allowing a quiescent period (24 hours) for settling does not appear to improve the supernatant quality as evidenced by the similarity of concentrations in the 60-watt reactor immediateley before and after the initiation of the six-day-per-week aeration. It was felt that the subsequent decline in supernatant concentration was due to the increased reactor liquid temperature during the summer. The reasons for the elevated supernatant concentrations at the 60-watt over the previous 37-watt setting was due to greater bottom sludge scour rather than hindered initial settling.

After 77 weeks of operation, a mass balance on the two aerated reactors was made accounting for COD input, effluent, and accumulation within the lagoon. The difference between input and the effluent plus accumulation was divided by the number of hours of operation and power rating to give the oxygen transfer rating of these aerators, Table 31. The calculated transfer was 1.7-1.8 kg O_2/hr/Kw which was about 80 percent of the manufacturer's rating of 2.1 kg O_2/hr/Kw.

FARM SCALE LAGOON

Full scale field lagoons were of necessity studied under conditions more closely following producer management. The producer lagoon system used in this study was jointly operated by North Carolina State University and the North Carolina Pork Producers Association and was

Table 31. OXYGEN MASS BALANCE FOR FIXED AERATOR OPERATING IN FIELD PILOT-SCALE REACTOR LOADED ONCE PER WEEK AT TWO TIMES THE REFERENCE RATE FOR SWINE WASTES

	Reactor X	Reactor Z
Operation period	a) 47 weeks, 7 days/week 60 watts. b) 20 weeks, 6 days/week 60 watts	a) 47 weeks, 7 days/week 37 watts. b) 20 weeks, 7 days/week 120 watts.
Aeration input based on manufacturer's rating 2.1 kg O_2/hr/kw, kg O_2	1,380	1,530
Oxygen demand in input, kg O_2	1,820	1,820
Oxygen demand in effluent, kg O_2	490	330
Oxygen demand in reactor, kg O_2	220	280
Oxygen demand unaccounted for, kg O_2	1,120	1,120
Oxygen transfer rate based on unaccounted COD	1.8 kg O_2/hr/kw	1.7 kg O_2/hr/kw

located near Raleigh. Lagoon operation was begun in 1961 in conjunction with a single concrete floor, totally roofed swine house. Wastes were flushed from the floor of each pen (1.4 m wide by 4 m long) into a gutter which sloped along the length of the house and emptied into the lagoon. The wastes were flushed to the gutter with a high pressure hose system once per day resulting in about 38 l of wastewater/d/45-kg hog. Swine were raised from approximately 20 kg to 100 kg in about 6-month intervals and then marketed much like a typical production unit. From 1961 to 1970 the average steady-state population was 160 hogs.

In 1971, an identical house and a second lagoon were constructed and the lagoons operated in series with the oldest lagoon being the first unit. From 1971 through 1972, swine production was similar to the previous years except that the average steady-state population was about 220 head. After January, 1973, the production unit was converted to a boar testing station. The upper one meter length of each pen was segregated and filled with shavings to reduce boar foot damage. Except for some spillage, these shavings were removed for land disposal after each testing cycle. The manure was removed primarily by scraping resulting in a volume reduction to about 11-15 l/d/45-kg hog. In terms of waste management, the hog population expressed as pounds of liveweight increases, peaks, and then declines on a twice-per-year basis.

The first lagoon is about 28 x 26 meters (730 m^2) with an original average liquid depth of about 1.2 m. This lagoon had been in operation since 1961, and had an average sludge depth of about 0.46-0.62 meters. Thus, there were about 362 m^3 of lagoon liquid volume. The daily liveweight contributing to this lagoon and the corresponding value of the supernatant TKN was evaluated, Figure 66, as well as the concentration pattern for COD and TOC over a fourteen-month period, Figures 67 and 68.

During both hog population cycles, the lagoon TKN supernatant concentration responded in rough sychronization with population liveweight and the response times were fairly rapid. The average weight present in these cycles was calculated by integrating the areas under the liveweight curve (Figure 66) and dividing by the total number of days. For the spring-summer period, the average liveweight was equivalent to 230-45-kg hogs while the fall-winter was equivalent to 220-45-kg hogs. Thus, the average lagoon loading is about 1.61 m^3 per 45-kg hog based on the current supernatant volume of about 1.4 times the reference rate used in this study. Based on the original lagoon volume (804 m^3), this waste loading rate was 3.6 m^3 per 45-kg hog or .6 times the reference loading rate (2.3 m^3/45-kg hog).

The supernatant concentration of TKN for the warmer spring-summer cycle was about 250 mg/l while for the fall-winter period about 350 mg/l. The median ambient air temperature for these periods was about 24°-C (spring-summer) and 10°-C (fall-winter). The difference in nitrogen concentration reflected the shift in equilibrium to ammonium ion and the decreased volatilization associated with lower temperatures. An on-farm lagoon monitored in Iowa evidenced a cold-warm shift in lagoon

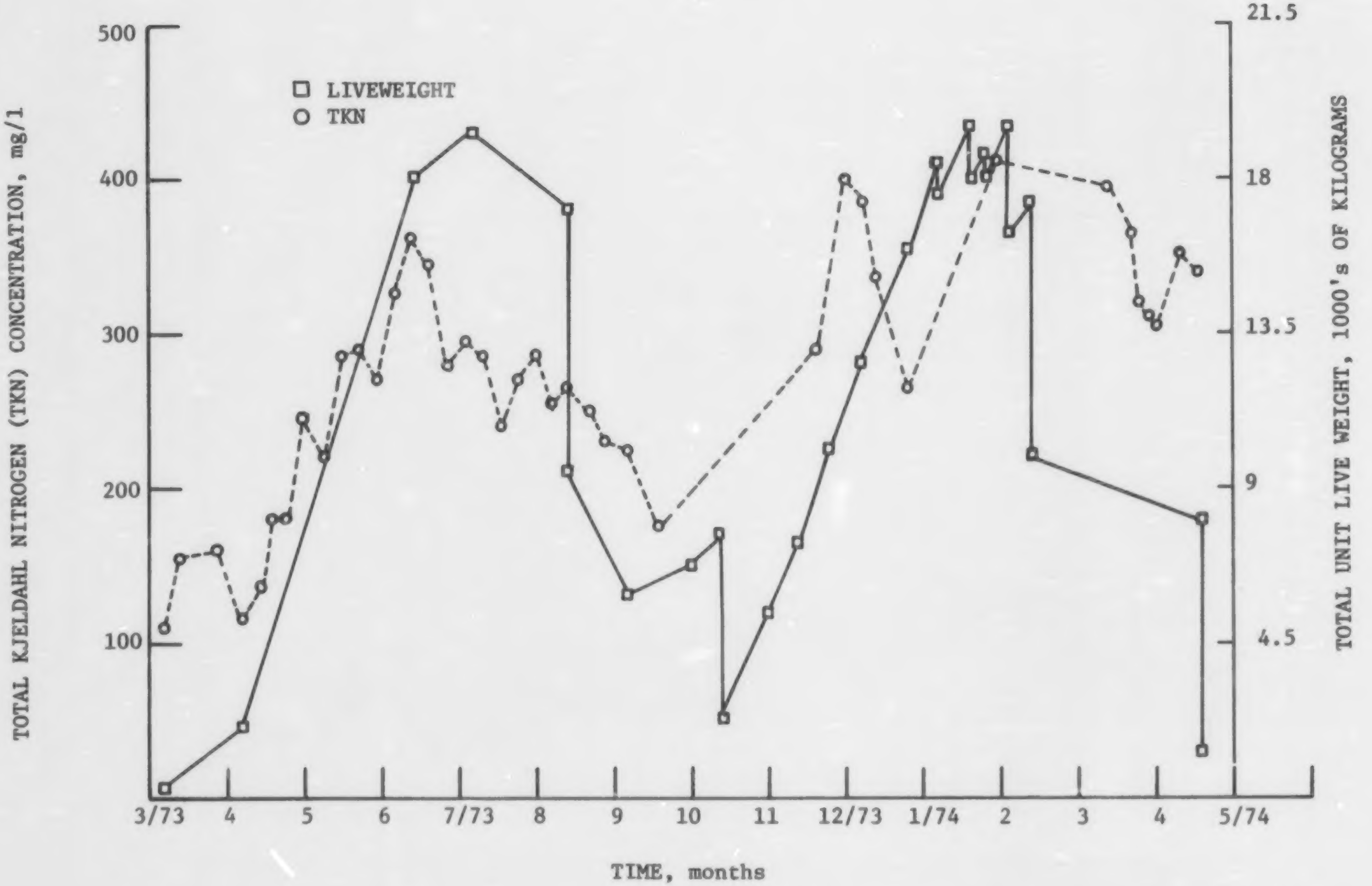


Figure 66. Supernatant TKN concentration and contributory liveweight changes for an on-farm swine waste lagoon loaded at once per day or more frequency (Clayton).

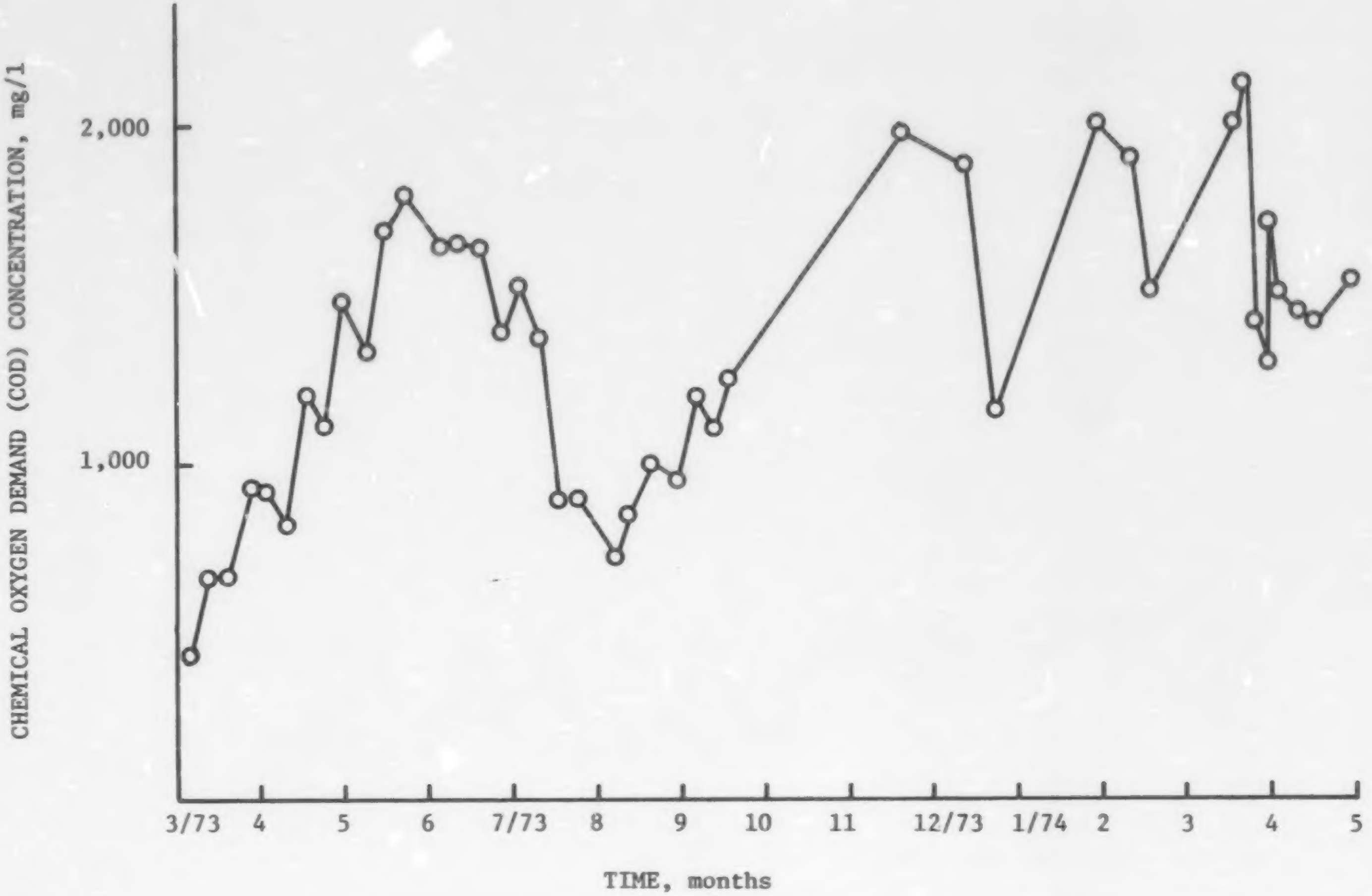


Figure 67. Supernatant COD concentration changes for an on-farm lagoon for swine wastes loaded at once per day or more frequency as waste material runs into lagoon.

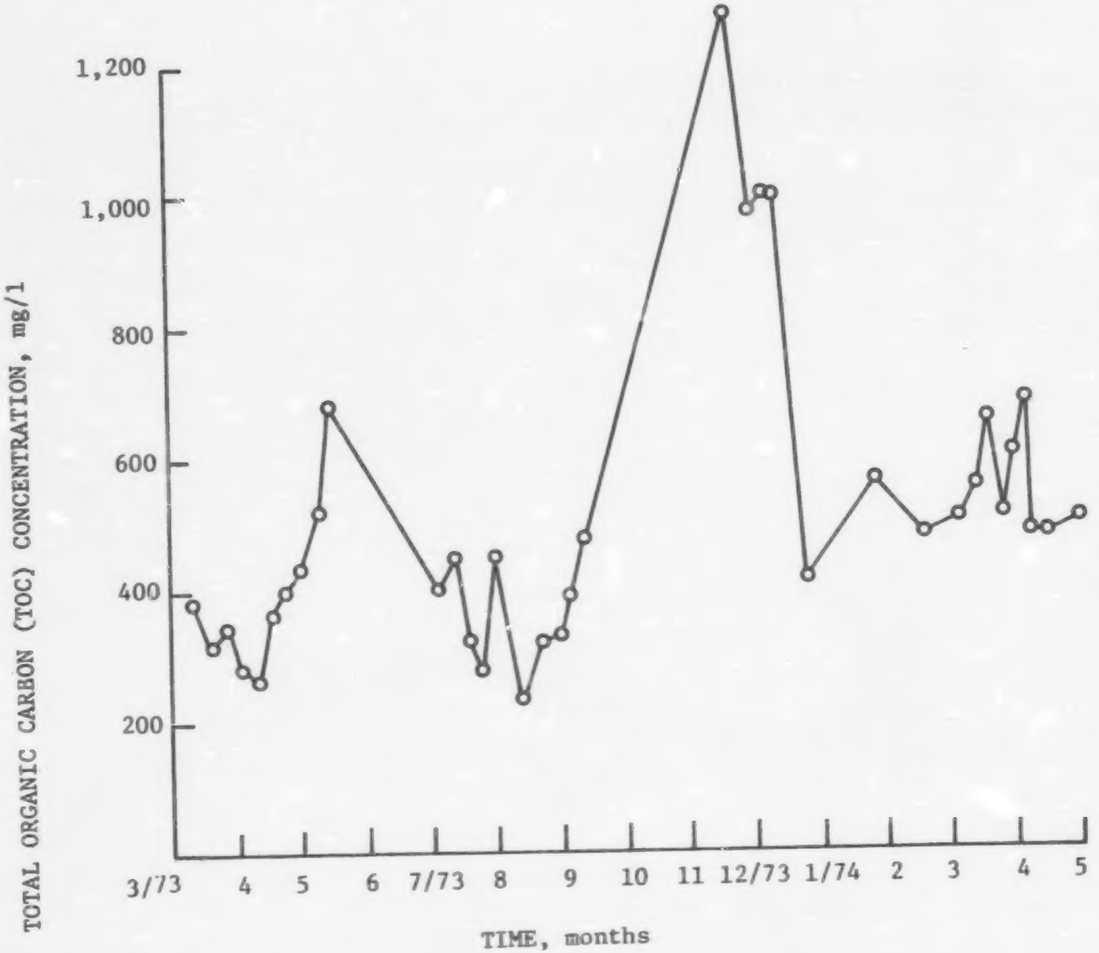


Figure 68. Supernatant TOC concentration changes for an on-farm lagoon for swine wastes loaded at once per day or more frequency as waste material runs into lagoon.

concentration of TKN and NH_3-N[82]. The reported winter to summer change of 650 mg/l TKN to 200 mg/l TKN for the Iowa situation was larger than the investigated North Carolina lagoon, probably due to the much colder Iowa winter period.

The farm-scale lagoon supernatant concentrations were compared to several field pilot units using the concentrations obtained during the winter-spring period 1974, Table 32. The farm-scale lagoon was comparable in supernatant concentration to the pilot unit loaded at 0.5 times the reference rate. This meant that the loading based on the original lagoon volume (0.6 times the reference) was similar to the pilot scale unit loaded at 0.5 times the reference rate. Thus, in terms of available volume, the farm-scale lagoon was similar to and had lower effluent concentration than comparably loaded field pilot units. The explanation for these lower steady-state concentrations for the farm-scale lagoon may have included the frequency of loading and the cyclic nature of the total waste load. From the laboratory experiments described earlier, it was determined that continuous loading at the lower input rates resulted in lower supernatant concentrations. This field lagoon was loaded daily and often the urine and some feces flowed continuously into the lagoon, thus resulting in nearly continuous loading. Also, the overall waste addition built up slowly as the hog population increased which would allow accumulation and development of a good biological population pursuant to lower effluent concentrations. Another important factor was the degradation which occurred prior to the waste being scraped into the lagoon. Because these production houses were more open to the air than enclosed houses over pits, there was added opportunity for waste degradation. This indicates the significant effect growing unit configuration and management can have on the swine lagoon waste load and thus supernatant concentrations.

Table 32. AVERAGE SUPERNATANT CONCENTRATION VALUES (JANUARY-APRIL, 1974) FOR FARM SCALE AND FIELD PILOT-SCALE LAGOONS RECEIVING SWINE WASTE

Lagoon	Lagoon volume m^3/45-kg hog	Concentration, mg/l			
		TKN	COD	TOC	$o\text{-}PO_4\text{-}P$
Farm scale	3.6	400	1,900	1,000	50
Field pilot scale					
reference rate	2.3	1,000	2,600	1,000	80
0.5 times reference rate	4.6	500	2,000	800	40

To test the possibility of concentration gradients in this lagoon, supernatant samples were taken at four circumferential positions, 3 meters from the shoreline and one in the lagoon center. At three of these sites, samples were taken at several points (Table 33). The variability was larger than for similar gradient studies in pilot scale lagoons; but the data verified that on the whole, the lagoon supernatant was reasonably uniform. Gradient conclusions for these test lagoons has been verified by recent sampling at other producer lagoons.

Table 33. ON-FARM SWINE LAGOON SUPERNATANT CONCENTRATION DISTRIBUTION IN VERTICAL AND HORIZONTAL DIRECTIONS (4/4/74)

Position Direction	Depth below surface, cm	Parameter concentration, mg/l		
		COD	TOC	TKN
North	15	1,470	700	320
East	15	1,540	660	210
South	15	1,300	700	300
	15	1,740	900	330
West	15	1,350	680	320
Center	15	1,820	660	300
	15	1,410	740	300

Since the initiation of waste management studies at this swine growing unit, the sludge depths have been measured on an occasional basis. Initially, sludge height was determined by the resistance offered to a flat object lowered into the lagoon or by the sludge adhering to a rod which was dipped into the lagoon. A boat was used to sample or take these rather approximate sludge measurements at various lagoon locations. Sludge depth was estimated by the average of five different sludge measurements taken around the lagoon. Overall sludge buildup from lagoon installation in 1961 until March, 1972, was about 2.5 cm per year. Since the depth measurements were begun on a more frequent basis (1972), the buildup appeared to be about 15 cm per year. Utilization of shavings for foot protection could have contributed to this increased rate. The 15 cm/yr rate would mean an 8-10 year period to fill a lagoon. This was longer than the 3-8 year period indicated by the laboratory experiment but similar to the filling time of 8-10 years projected for pilot-scale units loaded at the reference rate. Tentatively, then sludge buildup with swine lagoons loaded at the reference rate probably will lead to filling in 8 or more years. However, as noted, the primary field lagoon reported on herein had been in operation about 13 years and the present sludge depth was about 60 cm which indicated excellent sludge stabilization and compaction over long periods.

Anaerobic lagoon experiments were run in the laboratory, on a field pilot scale, and for a single, farm-scale unit. Direct transfer of results would not be feasible because of differences in temperature, size, and loading strategy; however, comparison of all experiments is useful for determining trends and lagoon characteristics. In general, laboratory experiments with Imhoff cones and 14 l reactors produced similar results in terms of supernatant quality. Comparisons of steady state supernatant concentrations for similarly loaded units during the winter-spring period showed that the COD and TOC concentrations of laboratory reactors were about one-third of the field pilot unit values. The TKN laboratory concentrations were about one-fifth of the field values; while the laboratory orthphosphates were about one-third to one-half of field units. Thus, direct transfer of effluent concentrations was not possible without some corrections for differences between experiments.

The uniformity of supernatant concentrations for various pollutional parameters in laboratory and field units ranging in size from one to over 850,000 liters was an unexpected result for which several possible explanations are available. The contribution of diffusion was calculated for point source diffusion into an infinite medium assuming the waste input was placed in one side or region of a reactor so that disturbances of total supernatant were reduced. This was reasonably true of the actual experimental procedure both in the laboratory and the field. From the standard chemical gradient diffusion models, the approximate time to attain uniform concentration by diffusion across a given distance is given by the ratio of the square of the diffusion distance divided by the diffusivity coefficient. The diffusion coefficient for organic molecules in aqueous solution is 10^{-6} cm^2/sec or smaller. Such diffusion across a meter of reactor would require 150 - 450 weeks. Thus, diffusion in these experiments represented a minor contribution to supernatant uniformity.

Daily temperature cycles and thus thermal induced currents were not considered as the principle explanation for uniformity since supernatant uniformity also occurred with laboratory reactors in a constant temperature environment.

Other mechanisms thus were postulated. Two reasonable explanations were a) high level of active biomass and b) mixing effects of microorganisms and liberated gas. As calculated earlier, the supernatant had large biological populations; thus, reactor gradients after loading could be rapidly reduced by microbial activities.

The continual mixing action of gas bubbles liberated with waste stabilization and supernatant microorganism movement could contribute considerably to uniformity of concentration. Micro mixing, as well as the gaseous eruptions commonly seen in large anaerobic reactors, would agitate the liquid and certainly promote uniformity.

Both laboratory and field pilot units showed the same trend of decreased supernatant COD, TOC, and TKN concentration with reduced swine waste loading. Supernatant TKN and TOC concentrations were directly proportional to loading rate at 2.3 m^3/45-kg hog or more for laboratory and field experiments. Thus, the effluent concentration for swine lagoons can only be estimated for a given loading rate.

Sludge COD, TOC, o-PO_4-P, and TKN concentrations were similar for all the experiments conducted, Appendix A1, A2, and A3. COD levels were 35,000 45,000 mg/l on an as-is basis in field and Imhoff cone studies with higher concentrations of 60,000-70,000 mg/l found at the higher loading rates. No conclusive evidence of concentration profiles within the well defined sludge zone were found as trends were conflicting in different reactors. Sludge TOC was generally 12,000-18,000 mg/l with TKN being 2,000-3,000 mg/l. These sludge COD, TOC, and TKN levels are close to the raw swine waste values. Sludge orthophosphate concentrations of 2,000-3,000 mg/l which were two to four times the raw waste value indicated settling and accumulation of phosphorus consistent with removal mechanisms discussed previously. Because the sludge values for the conservative constituent phosphorus were much higher than other parameters, it would be consistent to assume sludge decomposition and stabilization of organics and liberation of ammonium.

The sludge buildup for laboratory units loaded at the reference rate was from 15 percent to 35 percent of the lagoon volume per year. The field pilot-scale units had a sludge buildup of 10 percent to 15 percent of the lagoon volume per year for the reference loading. Buildup rate for the field unit was at best an estimate because of the variable input since startup. Effects of long-term compaction under controlled conditions for the pilot-scale units must be studied over a longer time period. However, at this time, it was concluded that sludge buildup for a lagoon loaded at the reference rate would necessitate lagoon cleanout at ten-year intervals or greater.

SECTION VI

PREDICTIVE AND INTERPRETIVE RELATIONSHIPS FOR LAGOONS

The aggregate data from the laboratory, pilot-scale, and on-farm experiments conducted in this study allowed certain simplifying assumptions to be made as a part of the development of predictive modeling relationships for lagoon performance and effluent quality. Models were useful in both interpreting data obtained from this study and allowing comparison of various experiments on a common basis. Modeling the investigated anaerobic reactors required certain assumptions to be made, mostly on a physical basis. The first assumption was that lagoons consisted of two distinct zones, the supernatant and the sludge. When material was put into a lagoon operating at steady state, distribution occurred within a certain time period between both zones. Additionally, during this time period and prior to the next loading event, some of the sludge material undergoing microbial reaction was liberated as by-products from the sludge to the supernatant. Therefore, in considering the two zones the initial input, transformations, and interfacial transfer between loading events could be used in mass balance equations. In terms of these lagoon studies, the net amount of material entering the supernatant was taken to be the initial unsettled fraction of the raw swine waste plus the resuspension of sludge components while the ultimate material remaining in the bottom zone was considered sludge.

Lagoons may be operated with no continuous overflow; or, if part of a series treatment system, lagoon overflow into another unit may exist. No continuous discharge was the lagoon management scheme used for the majority of these laboratory and field experiments. Based on the absence of substantial supernatant concentration gradients in laboratory, pilot-scale, and field units (excepting the very heavy loading of four times the reference rate), the second assumption was that the lagoon supernatant zone was well-mixed and hence at uniform concentration. Reasons contributing to lagoon supernatant uniformity included loading procedures, thermal and wind mixing, gas evolution and bubbling, and microbial activity. The mechanisms and magnitude of these phenomena varied considerably between experiments but for predictive purposes the lumped effect was that the supernatant zone behaved as a well-mixed reactor.

The no discharge lagoon criterion necessitates liquid removal in moisture excess regions because lagoons have a finite liquid capacity. Usually a pump-irrigation or a tank wagon system is employed to remove supernatant liquid on a periodic basis. Over long time periods, the average overflow will equal the in-flow minus any evaporative or other losses. Under these operating conditions, the residence time in the lagoon closely approximated the design equation:

$$T_r = V/Q \tag{3}$$

where T_r = residence time, weeks

V = lagoon or reactor volume, liters

Q = waste input rate, liters/week

If continuous or semi-continuous overflow existed, there would be potential for nonuniform conditions or incomplete mixing[42] due to short circuting or surface streaming. This would lead to shorter and more variable residence times. However, if influent and effluent pipes were located as far apart as possible or if baffle construction was used, then short circuiting would be prevented and lagoon residence would approximate the theoretical retention time. The well-mixed assumption would then be more valid and the lagoon supernatant more uniform.

With these two primary assumptions the standard constant-stirred tank reactor analysis could be applied to anaerobic lagoons. A continuous and a batch loading approach was considered since the lagoon operation had elements of both schemes.

It should be noted that the employed models are predominately empirical in nature and that as data on annual cycles become available models can be expanded to better predict lagoon effluent quality.

BATCH LOADING APPROACH

The actual operation of the pilot-scale units and most of the laboratory reactors was batch loading, usually on a once-per-week basis. Prior to each loading, samples were taken and material was drained to restore the constant reactor design volume; e.g., 14 liters for the cylindrical laboratory reactors. These experimental units were nonoverflow, and immediately after loading the supernatant concentration would rise reflecting the kilograms of parameters added and the dilution effect of the lagoon liquid, Figure 69. Settling distribution would then occur followed by the various anaerobic reaction processes operational over

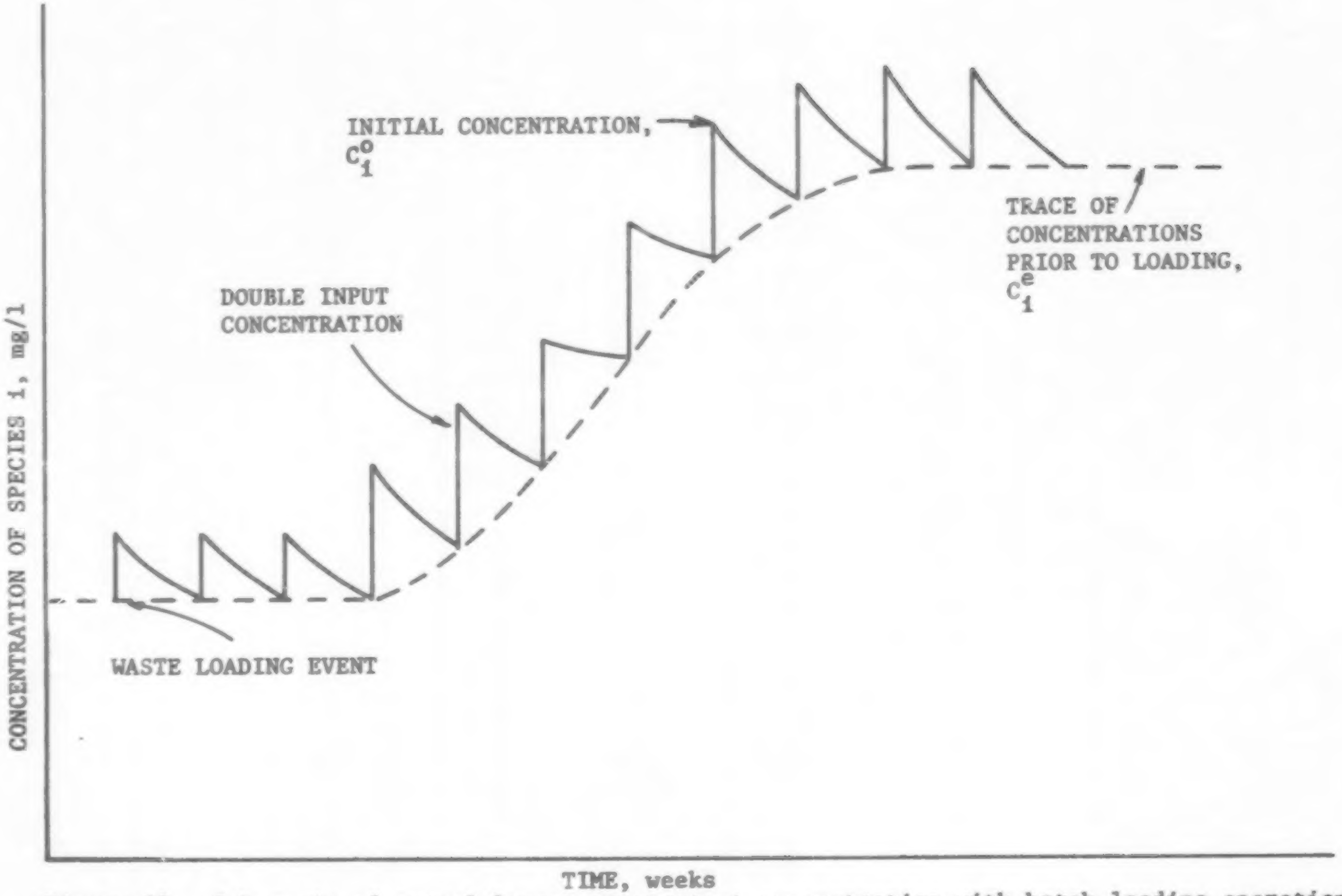


Figure 69. Schematic of actual lagoon supernatant concentration with batch loading operation.

the period between loading. Thus, a mass balance on any constituent, i, which remains in the supernatant after initial settling was:

$$V \frac{dC_i}{dt} = -k_B C_i V \qquad (4)$$

with $C_i = C_i^o$ when $t = o$

where C_i = concentration of species i in the supernatant, mg/l

C_i^o = initial concentration of species i in supernatant, mg/l

k_B = removal rate constant, batch system, weeks^{-1}

t = time, weeks

The term on the left is the rate of change of the amount of species i with respect to time, which for a constant volume system is actually the concentration change, grams or gram moles per unit time per unit volume. The term on the right represents the disappearance of species i, assumed to occur at a rate proportional to the amount present in the supernatant, VC_i; i.e., the more material present the faster the rate of disappearance. This is referred to as first-order kinetics and is often substantiated by natural systems. The proportionality constant, k_B, will vary primarily with reaction species and temperature.

The first-order reaction and the batch-reaction constant, k_B, can be interpreted as the lumped summation of the various anaerobic pathways by which long-chain organic compounds characteristic of raw swine waste are degraded. This breakdown can be indicated by a change in COD, the oxygen equivalent required to convert a given carbon compound to complete stabilization end products of carbon dioxide and water. In general a decrease in COD would indicate a conversion to more oxidized and shorter-chain compounds, but it does not necessarily indicate a loss of organic carbon from the system. The total organic carbon (TOC) does directly represent carbon content, excluding inorganic forms and thus changes in the TOC do reflect actual system losses, primarily as carbon dioxide and methane. If organic carbon converted to carbon dioxide stayed in solution because the liquid was unsaturated, there would be an apparent loss of total organic carbon but actually only a change in chemical component form. However, the amount of inorganic carbon dissolved and measured in all lagoon samples was small compared to the organic carbon concentration indicating that TOC reductions actually indicated supernatant carbon losses. Therefore, both TOC and COD are useful parameters which change value much the same as the concentration of the actual chemical reactants participating in the ongoing anaerobic reactions.

Equation 4 was integrated under steady operation conditions to yield the change in supernatant concentration with respect to time between one loading event and another. The integrated form was:

$$C_i = C_i^o \exp(-k_B t) \qquad (5)$$

where t varied from zero immediately after loading up to the time of the next loading event; e.g., one week. The initial concentration, C_i^o, was calculated from a mass balance immediately after loading. The concentration of species i just prior to loading, the volume and concentration of the raw waste input, and the volume of the reactor were the needed parameters. Any liquid volume input which was not matched by evaporative losses was drained prior to loading to maintain a constant volume over long periods of operation. This mass loss equaled the effluent volume, E, times the supernatant concentration, C_i^e, with E ranging from zero to the feed volume. The effluent concentration was quite small compared to the input so without a large error the effluent and input volumes were set equal. Thus, the initial concentration of species i was:

$$C_i^o = \frac{VC_i^e + C_i^f F - \alpha_i C_i^f F - C_i^e F}{V} \qquad (6)$$

where C_i^e = supernatant concentration of species i at the end of the reaction period just prior to waste loading, mg/l

C_i^f = concentration of species i in raw waste input, mg/l

F = waste input and effluent volume, liters

α_i = net fraction of waste input settled

Consider first the case where the loading frequency was constant; e.g., once per week. During steady operation with constant waste input, concentration and volume, the initial concentration (C_i^o) and final concentration (C_i^e) would remain the same from batch to batch. To evaluate k_B under these conditions, Equation 6 was substituted into Equation 5 using $t = 1$ week so that $C_i = C_i^e$. Additionally, $\beta_i = 1-\alpha_i$ or represents the fraction of waste input remaining in the supernatant. The resulting equation was:

$$C_i^e = \left[C_i^e + \left(\beta_i C_i^f - C_i^e\right)\frac{F}{V}\right]\exp(-k_B \cdot 1 \text{ week}) \qquad (7)$$

where $\beta_i = 1-\alpha_i$

after rearranging Equation 7 becomes

$$\exp(k_B \cdot 1 \text{ week}) = 1 + \frac{\beta_i C_i^f - C_i^e}{C_i^e}\,\frac{F}{V} \qquad (8)$$

$$\exp(k_B \cdot 1 \text{ week}) - 1 = \frac{\beta_i C_i^f - C_i^e}{C_i^e}\,\frac{F}{V} \qquad (9)$$

The value of the batch reaction rate, k_B, was calculated for TOC and COD for laboratory reactors (14-1) loaded at several input rates during the steady-state operational period, Table 34.

Table 34. FINAL CONCENTRATION AND BATCH REACTION RATE CONSTANT FOR LABORATORY ANAEROBIC SWINE REACTORS (14 1)

Fraction or multiple of reference rate	C_i^e, mg/l		k_B, weeks^{-1}	
	TOC	COD	TOC	COD
4.8	2,100	4,000	.50	.69
1.2	400	1,000	.67	.74
.6	275	500	.53	.74
.3	100	350	.48	.59
Average			.54	.69

The constants, k_B, showed relatively little change over the sixteen-fold range of loading rate. The laboratory average ambient temperature was 22° C ± 1.5°C.

From these data it was concluded that the various loading rates in themselves did not affect the microbial activity in these small reactor units. A change in reaction constant could indicate some toxic effect or for reactors on the border of anaerobic and aerobic conditions, a change in microbial populations, metabolic kinetics, and end products. Therefore, with k_B constant the implicit dependence of effluent supernatant concentration on loading rate was:

$$\frac{C_i^e}{\beta_i C_i^f - C_i^e} = \frac{F}{V\left[-1 + \exp(k_B \cdot 1 \text{ week})\right]} \tag{10}$$

Because the raw swine waste was very concentrated, $C_i^e << \beta_i C_i^f$, and thus:

$$C_i^e = \frac{\beta_i C_i^f F}{V\left[-1 + \exp(k_B \cdot 1 \text{ week})\right]} \tag{11}$$

The demoninator was constant for a given species as was C_i^f for a steady-state waste input so that the effluent TOC or COD concentration was linearly dependent on the feed volume which agreed with data, Figure 70, for the laboratory swine units. The effluent concentration for another waste type under similar reactor conditions can be calculated by equation 11 if the reaction constant (k_B) is known.

The batch-loading model describes the actual weekly operation of these anaerobic lagoon experiments. It has some capability to predict the effect of aperiodic loading because the time between inputs can be changed in a straightforward manner in Equation 5. Additionally, variable input volume and concentration can be taken into account.

There were, however, several disadvantages in this batch-loading approach. The first limitation was that the net settling effect had to be included in a circumlocutory manner by means of the hypothetical initial phase separation condition, $\alpha_i C_i^f$. A second disadvantage was that transient conditions which had an impact for longer than one loading period such as a change in loading concentration or loading rate and changes in volume associated with large lagoon drawdowns, could only

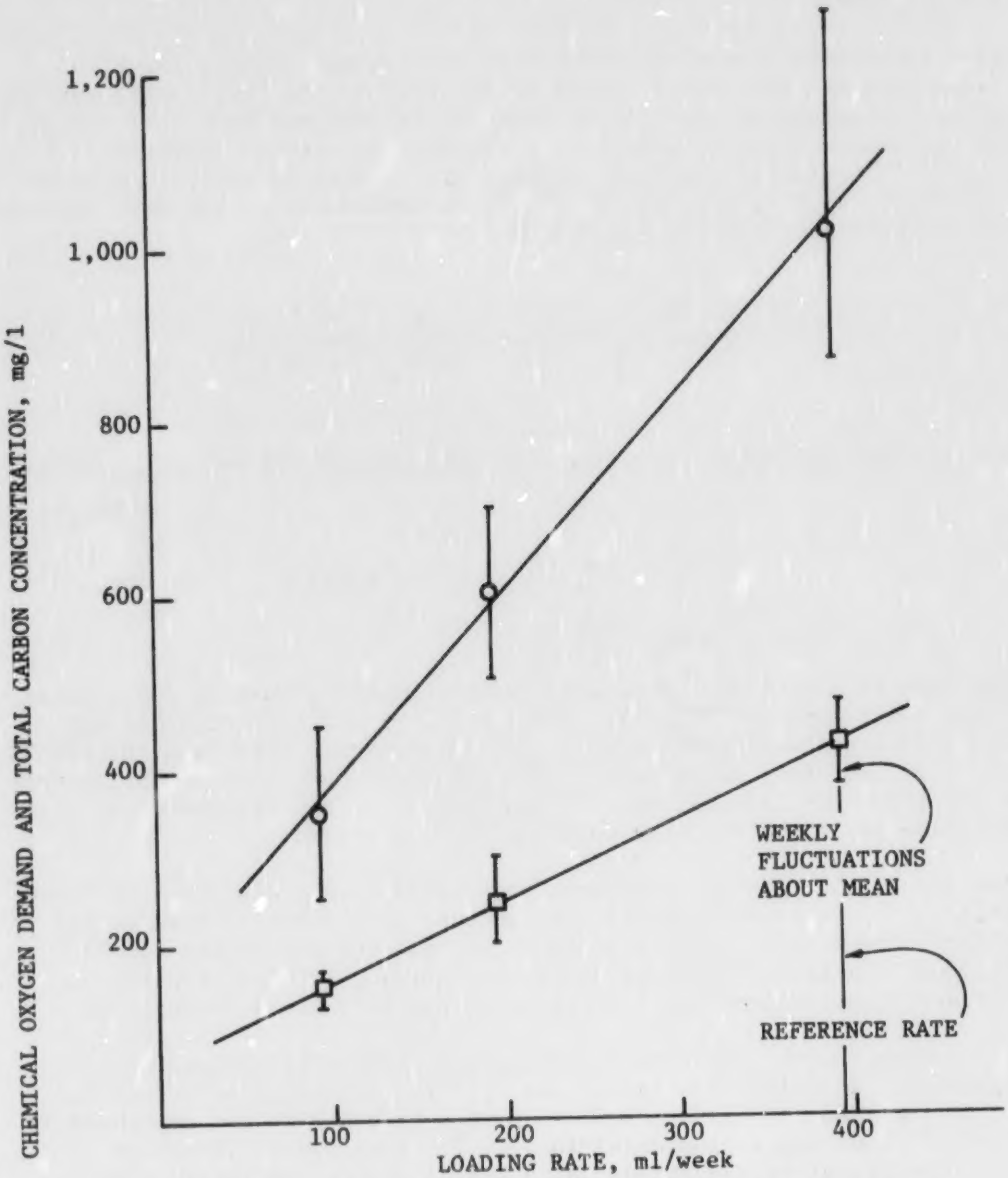


Figure 70. Steady-state supernatant COD and TOC concentrations for laboratory reactors (14 liters) loaded once per week with swine waste (44,000 mg COD/1, 15,000 mg TOC/1).

be determined by a number of successive weekly calculations. The transient condition resulting from a changed loading volume depicted in Figure 69 is descriptive of the successive calculations needed. This latter limitation prevented rapid prediction of steady-state conditions associated with management options in lagoon operation. Some of these disadvantages could be overcome with a continuous-stirred tank reactor modeling approach.

CONTINUOUS LOADED APPROACH - ORGANICS

The development of a continuous model required one assumption in addition to the two primary assumptions made earlier. This assumption was that when the overall month by month operation was considered, the overall loading rate was simply ($C_i^f \cdot Q$) kg per week (where Q is the waste input in l/wk), regardless of the actual time span of loading. In other words, over months of operation there was little difference in how or over what period of time the loading occurred as long as the time period between loading was short in comparison to the time period to be modeled. This assumption was substantiated by the laboratory reactor data discussed earlier showing little difference in supernatant concentration over a wide range of batch loading frequencies, Figures 25 and 26. The slight supernatant concentration difference observed in units which actually were loaded continuously would simply change some of the equation rate constants but not affect the general model.

The continuous loading equation describing the supernatant of an anaerobic reactor included parameter accumulation, inflow, outflow, removal via settling, and removal or generation by microbial or chemical reaction. The inflow, outflow, and accumulation were standard terms. The initial settling removal was assumed to be rapid in comparison to the overall time available for reaction and accumulation. This appeared valid because several workers including Jett et al.[80] found settling of various raw swine waste constituents was essentially complete in one hour, and investigated loading frequencies were on the order of once per week. It was further assumed that for each species i, of a given waste stream, the amount settled was a constant fraction (α_i) of the raw waste input. If the microbial populations had acclimated, then the net settled fraction could be used; i.e., initially settled component minus the amount remineralized from the sludge to the supernatant. The constant net settling assumption appears to be verified by the uniform amount of raw waste parameters found in sludge over various lengths of storage.

Component removal via reation was assumed to follow first order kinetics as with the previous model; i.e., the reaction occurred at a rate proportional to the amount of species i present. Correspondingly, the chemical oxygen demand and total organic carbon were the parameters used to reflect the stabilization and loss of organic material and were assumed to be removed at a first-order rate.

A mass balance for species i under unsteady conditions for a uniformly mixed reactor with balanced inflow and outflow yields:

$$V \frac{dC_i}{dt} = QC_i^f - QC_i - k_i'C_iV - \alpha_iQC_i^f \qquad (12)$$

with $C_i = C_i^o$ when $t = o$

where C_i = reactor supernatant concentration of species i, mg/l

C_i^o = supernatant concentration at the start of the modeling period, $(t = o)$, mg/l

Q = flowrate, liter/week

k_i' = reaction or removal constant, week^{-1}

The stabilization or reaction constant k_i' would be dependent primarily on the parameter being considered as well as the temperature and type of waste. The net fraction settled, α_i, was as defined above in the discussion of sludge accumulation.

More sophistication could have been included in Equation 12 by adding terms which represent additional loss or generation mechanisms. For example, the sludge-supernatant transfer could be added as a pathway for increasing the amount of material entering the supernatant between batch loading events to more closely describe actual lagoon operation. To do this, the initial rather than net fraction settled would be represented as α_i. This supernatant addition from the sludge was not included because it involved the evaluation of two unknowns, the initial settling and the sludge-supernatant interfacial exchange rates. Overall, the net settling and the coefficient α_i take both of these phonemena into consideration. Evaporation or rainfall volume change effects on concentration were not included because of the small losses or gains found as compared to the raw waste inputs. More detailed reaction models reflecting the microbial nature of waste stabilization (e.g., Michaeles-Menten kinetics) were not used because routine monitoring did not include microbial counts and the complexity of such a model would exceed control possibilities for the investigated swine lagoons.

Certain anaerobic lagoon performance characteristics can be evaluated by considering the limiting cases of Equation 12. The first such case involved the variation of concentration with time for lagoons if the lagoon was simply a body of water used for waste storage and there were no microbial or chemical removal mechanisms. In colder regions there are periods when storage is in fact the only lagoon function because anaerobic activity and liquid volatilization are essentially zero.

If a lagoon were serving only for storage, either because low temperature, some toxic material or shock waste input have prevented microbial activity, then this implies that the reaction rate constant k_i is zero. Assuming no microbial activity, initial settling would still take place, but there would be no further sludge-supernatant transfer; thus, α_i would represent both the initial and total fraction settled. Integrating equation 12 under these assumptions and subject to a constant initial condition yields:

$$C_i = \beta_i C_i^f + \left[C_i^o - \beta_i C_i^f\right]\exp(-Qt/V) \qquad (13)$$

where $\beta_i = 1 - \alpha_i$

Several consequences of this solution were noteworthy. The first was the time required to attain steady-state supernatant concentration, defined as the time required to reach 99 percent of the steady-state concentration. The second term on the right in Equation 13 decreased exponentially as time increased; hence it was a transient term. Initial concentration in these studies was zero or very low when compared with the raw waste input. The time at which the supernatant concentration, C_i, was 99 percent of the steady-state, $\beta_i C_i^f$, was calculable by solving for t:

$$\frac{.99\ \beta_i C_i^f - \beta_i C_i^f}{-\beta_i C_i^f} = \exp(-Qt/V) \qquad (14)$$

$$.01 = \exp(-Qt/V)$$

$$4.6\,\frac{V}{Q} = t \qquad (15)$$

At the reference loading rate (2,300 l reactor volume/45-kg hog) and a swine waste volume of 7.5 l/day/45 kg hog, solving for t yields:

$$t = \frac{2,300 \text{ l/hog}}{7.5\text{l/hog/day}} \cdot 4.6 = 1,410 \text{ days} \approx 3.9 \text{ years}$$

Thus, a long transient or start-up period of almost four years would be expected for a storage-only lagoon. Correspondingly, if the waste input concentration was held constant for lagoons loaded at different rates over the time periods necessary to achieve steady-state, then this transient or start-up time should be inversely proportional to the loading rate, Q, Equation 15. These times would range from 3.8 to 122 years as the loading varied from the reference to one thirty-second of the reference rate used in this study. Comparing these deductions with the pilot scale lagoon data, Figures 41 to 58, it follows that transient times are from 10 to 1000 times more rapid than could be accounted for by settling alone. Also, for most of the loading rates investigated the transient times were the same; i.e., independent rather than inversely dependent on the loading rate.

A second consequence of Equation 13 is that at steady-state, with the transient term insignificant, the supernatant concentration is:

$$C_i^{ss} = \beta_i C_i^f \qquad (16)$$

where C_i^{ss} = steady-state concentration of species i, mg/l

The ultimate or net fraction of COD settled in the laboratory studies was about 25 percent, so the steady supernatant concentration should be $(1-.25) \cdot C_{COD}^f$ or 30,000 mg/l for a feed strength of 40,000 mg COD/l. Thus, all the units loaded at different rates should attain the same steady-state supernatant concentration, equation 16. Supernatant concentrations from the laboratory and field reactor data were much lower than 30,000 mg COD/l and evidenced a decrease in concentration as the loading rate was decreased.

Differences between these experimental results and the predicted values of transient times and steady-state supernatant concentrations for storage lagoons indicated that much more was involved in an actively functioning animal waste lagoon than included in postulated models; and thus, another loss mechanism must be the significant factor in lagoon performance. Also if the COD supernatant concentration for a swine waste lagoon was above 30,000 mg/l, then it could be concluded that the lagoon was not functioning biologically. This then could be used as a criterion for lagoon failure based on supernatant COD concentration.

Integration of Equation 12 developed earlier with a first-order reaction loss term and a constant initial condition, C_i^o yielded:

$$C_i = \frac{Q}{Q + k_i} \beta_i C_i^f + (C_i^o - \frac{Q}{Q + k_i} \beta_i C_i^f) \exp \left[-(Q + k_i)t/V\right] \quad (17)$$

where $k_i = k_i' \cdot V$, liters/week

The reaction rate constant k_i is specific for the species monitored, i. Two undetermined constants β_i, the settling component, and k_i the first-order removal component existed. Since β_i did not appear in the time dependent decay term, $\exp\left[-(Q + k_i)t/V\right]$, then data for both the transient response and the steady-state operation would be needed to determine β_i and k_i.

The solution for the supernatant concentration, C_i, was composed of a steady-state and transient term, the first and second terms on the right of Equation 17, respectively. The transient term was an exponential decay function where the rate of decay was given by the term $(Q + k_i)t/V$. Expanding and rearranging the exponential power gives:

$$\left[\frac{Q}{V} + \frac{k_i'V}{V}\right] t = \left[\frac{1}{T_r} + k_i'\right] t \quad (18)$$

The reaction constant k_i' has units of reciprocal time and can be visualized as the inverse of a characteristic time for the reaction involving the gain or loss of species i. The exponential power was thus:

$$\frac{t}{T_r} + \frac{t}{T_{rxn}} \quad (19)$$

where $T_r = V/Q$ = bulk fluid residence time, weeks

$$T_{rxn} = 1/k_i', \text{ weeks}$$

The larger this exponential power expression in Equation 19, the more rapidly the system approaches steady-state. As shown with the storage model, the ratio of real time to the characteristic residence time (t/T_r) was a small term since T_r was on the order of years for the investigated swine lagoons. Therefore, it was expected and subsequently verified that the ratio of real time to characteristic reaction time (t/T_{rxn}) was large since the total time from start-up to steady-state was about 10-20 weeks for the investigated anaerobic lagoons or reactors, Figures 4-17. Physically, the interpretation of the exponential constants is that the microbial reactions take place over short intervals, especially in comparison with common lagoon residence times.

The steady-state supernatant concentration derived from Equation 17 was related to the input concentration as follows:

$$C_i^{ss} = \frac{Q}{Q + k_i} \beta_i C_i \qquad (20)$$

The predicted steady-state supernatant concentration was dependent on the loading rate with a lower concentration expected at the lower loading rate. A parametric graph of this relation is given in Figure 71 for constant $\beta_i C_i^f$ and increasing values of k_i.

A plot of laboratory reactor (14 l) COD supernatant values versus loading rate, Figure 70, indicated a nearly linear relationship. The value of k_i was calculated from Equation 20, Tables 35 and 36, after first determining β_i which is equal to $1 - \alpha_i$ where α_i is the net fraction settled or remaining in the sludge. From the laboratory Imhoff cones and cylindrical 14 l reactors, the ultimate sludge accumulation of the total waste input for the 10-30 week periods of this experiment was about 30 percent for COD and 25 percent for TOC. Thus:

$$\beta_{COD} = 1 - .3 = .7$$

$$\beta_{TOC} = 1 - .25 = .75$$

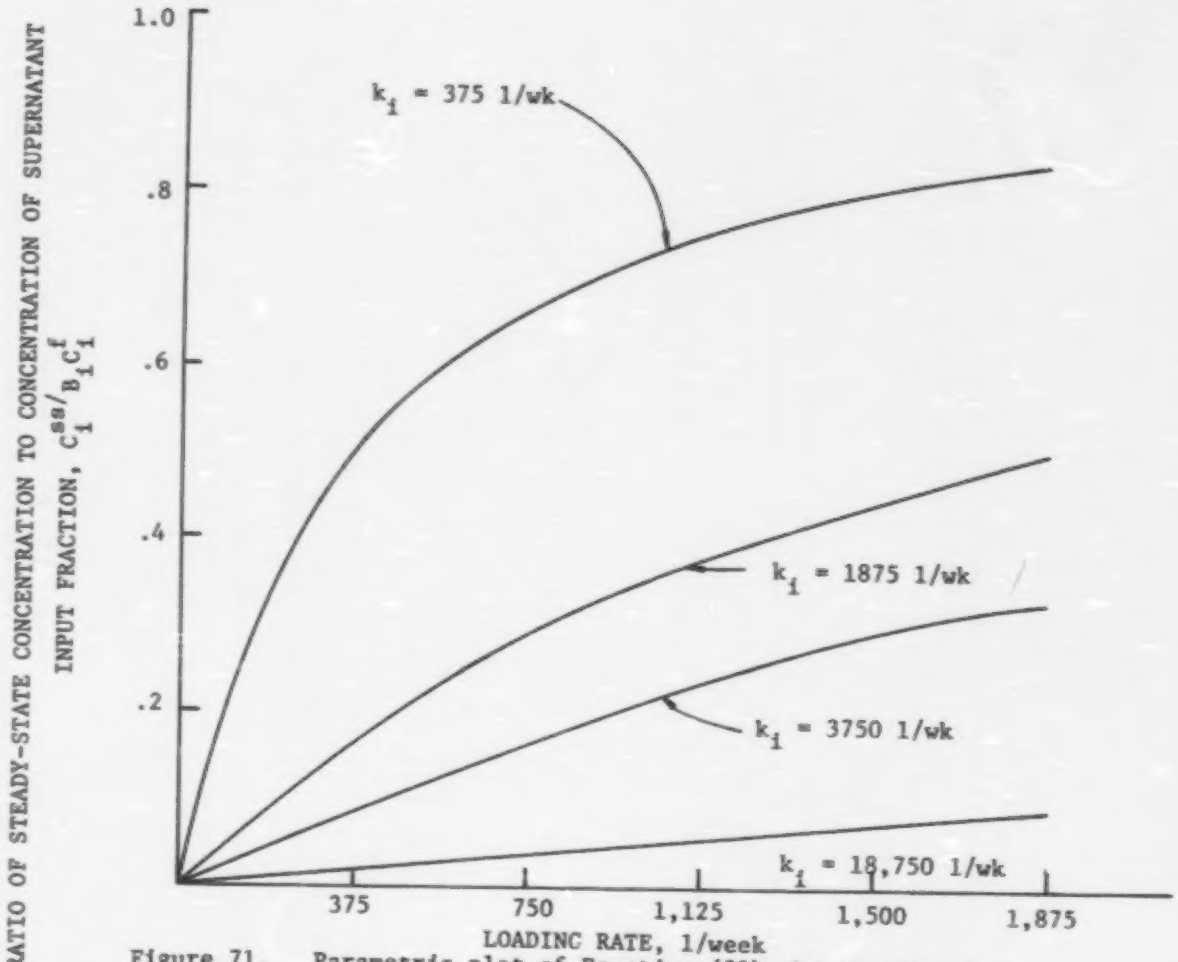


Figure 71. Parametric plot of Equation (20) showing linear dependence of steady-state concentration on loading rate at high reaction rate constants.

With these values the reaction rate constants, k_i, were calculated, Tables 35 and 36. The units of k_i are liters per week which when compared to the input loading rate, Q, shows that $Q << k_i$. With this inequality equation 20 simplifies to:

$$C_i^{ss} = \frac{Q}{k_i}\,\beta_i C_i^f = \frac{Q}{k_i^{'}V}\,\beta_i C_i^f = \frac{QC_i^f}{K_i} \qquad (21)$$

so that the ratio of k_i/β_i which is still a constant, can be redefined as K_i and is thus the only unknown to be calculated. Because β_i was determined from separate measurements in these experiments, there was no inherent advantage in using either K_i or k_i, but for other situations the use of K_i should be more advantageous. Both constants are listed in Tables 35 and 36.

From the comparison of the rate constants for chemical oxygen demand and the total organic carbon, both representative of lagoon organic matter, it was seen that indeed the reaction rate constants were very similar, Tables 35 and 36. This reemphasized the fact that either parameter could be substituted for the other in a monitoring or modeling scheme. The parameter chosen then would be dictated by the analytical facilities available.

The very high reaction rate constant in comparison to the input volume emphasized that reaction times are small compared to lagoon residence times. Thus, there were large reductions in raw waste concentrations. Under these conditions the error in β_i, when β_i is near 1.0, was not great. Calculations showed that when β_i varied between 0.7 to 1.0, the predicted ratio of effluent concentration to influent concentration ranged from 97.0 to 95.7 percent. Therefore, the net amount settled with raw swine waste was so low that the effect was insignificant. With another waste type yielding a greater settled fraction, the errors in measuring α_i may be sufficiently large that the use of the lumped parameter $K_i = k_i/\beta_i$ would be warranted over the coefficient k_i.

Values of the reaction rate constant for laboratory units should be capable of scale-up into a predictive equation for the pilot-scale field units because the raw waste input was the same for both experiments. However, a correction for temperature must be included. The traditional relationship of doubled biological activity or microbial reaction rate with a 10° rise in temperature was used because kinetic data at several temperatures were not taken. The laboratory units were controlled at 26° C ± 1.5° C while the field lagoon supernatant values were evaluated during February to April, 1974, when the average lagoon temperature was

Table 35. FIRST-ORDER REACTION RATE CONSTANTS FOR CHEMICAL OXYGEN DEMAND (COD) IN ANAEROBIC SWINE LAGOON UNITS

	Laboratory (14 1)			Pilot scale			Extrapolated from laboratory to field units
Fraction of Reference Loading Rate	k_{COD} equation (20), 1/wk	k'_{COD} (β=.7) equation (21), week^{-1}	K_{COD} equation (21), 1/wk	k_{COD} equation (20), 1/wk	k'_{COD} (β=.87) equation (21), week^{-1}	K_{COD} equation (21), 1/wk	k'_{COD} (β=.87), 11° C equation (21), week^{-1}
1	8.6	.61	12.2	6,000	.34	6,638	.27
.5	8.0	.57	11.4	3,830	.22	4,295	.26
.25	7.0	.50	10.0	2,400	.14	2,733	.22
.125				2,250	.13	2,538	
.0625				2,000	.11	2,148	
.031				2,000	.11	2,148	

Table 36. FIRST-ORDER REACTION RATE CONSTANTS FOR TOTAL ORGANIC CARBON (TOC) IN ANAEROBIC SWINE LAGOON UNITS

	Laboratory			Pilot scale			Extrapolated from laboratory to field units
Fraction of Reference Loading Rate	k_{TOC} equation (20), 1/wk	$k'_{TOC}(\beta=.75)$ equation (21), $week^{-1}$	K_{TOC} equation (21), 1/wk	k_{TOC} equation (20), 1/wk	$k'_{TOC}(\beta=.84)$ equation (21), $week^{-1}$	K_{TOC} equation (21), 1/wk	$k'_{TOC}(\beta=.84)$ 11° C equation (21), $week^{-1}$
1.0	9.0	.64	11.9	4,440	.25	5,050	.26
.5	7.8	.55	10.3	3,600	.20	4,040	.22
.25	6.5	.47	8.8	2,500	.14	2,830	.19
.125				2,200	.12	2,430	
.0625				1,900	.11	2,220	
.031				1,600	.094	1,900	

11° C ± 5.5° C, Appendix B1. This temperature differential translated into a difference in rate factor of 2.8 between laboratory and field units. The reaction constants k_1 and K_1 calculated from the laboratory, laboratory adjusted to field temperature, and the measured pilot-scale field conditions are given in Tables 35 and 36. The predicted and actual supernatant concentrations of the field units as a function of the weekly loading rate are given in Figures 72 and 73. The predicted concentrations were too high indicating that the field units were slightly more efficient than the laboratory units when put on the same temperature basis. However, in light of the large number of assumptions about kinetic temperature dependence, settling values, and validity of a direct scale-up approach, the agreement between experiments was not unreasonable.

The value of the kinetic rate constants for the field units was less consistent among the various loading rates than the laboratory data, especially when comparing the higher and the lower loading extremes. This inconsistency emphasized that the model was only an approximate approach and that the actual lagoon functioning was more complex. Another laboratory-field difference was the fraction settled, α_1. After about 120 weeks the three pilot-scale field units measured for sludge depths, Table 25, had approximately 12 percent of the input volume which remained settled whereas the laboratory units tested had a value of about 25 to 30 percent. The reasons for these differences are not known at this time, but one factor may be the longer duration of the field units.

Comparison of the rate constants derived from the laboratory and the field units, Tables 35 and 36, indicated that the field data were less consistent over the range of loading rates than the laboratory units. Only the field units with the lower loading rates of .25 to .031 times the reference had rather similar and consistent rate constants. If the average removal rate from these lower loading inputs was used to predict the COD and TOC supernatant concentration, Figure 72, then the measured concentrations would be lower than predicted. This may indicate some greater microbial response at higher loading rates which possibly could be predicted with more detailed biochemical data and a more sophisticated model. The predicted supernatant concentrations for the various average k_1 values measured are also shown in Figures 72 and 73.

On an overall basis, the use of an average reaction rate constant as determined in the laboratory (and temperature corrected) or from a field experiment at a single loading rate gave a good approximate order-of-magnitude value for the supernatant concentration of organic matter as represented by COD and TOC. The prediction of supernatant TOC concentration was better than that for COD for reasons not yet fully explained. The extensive range of oxidation states for organic

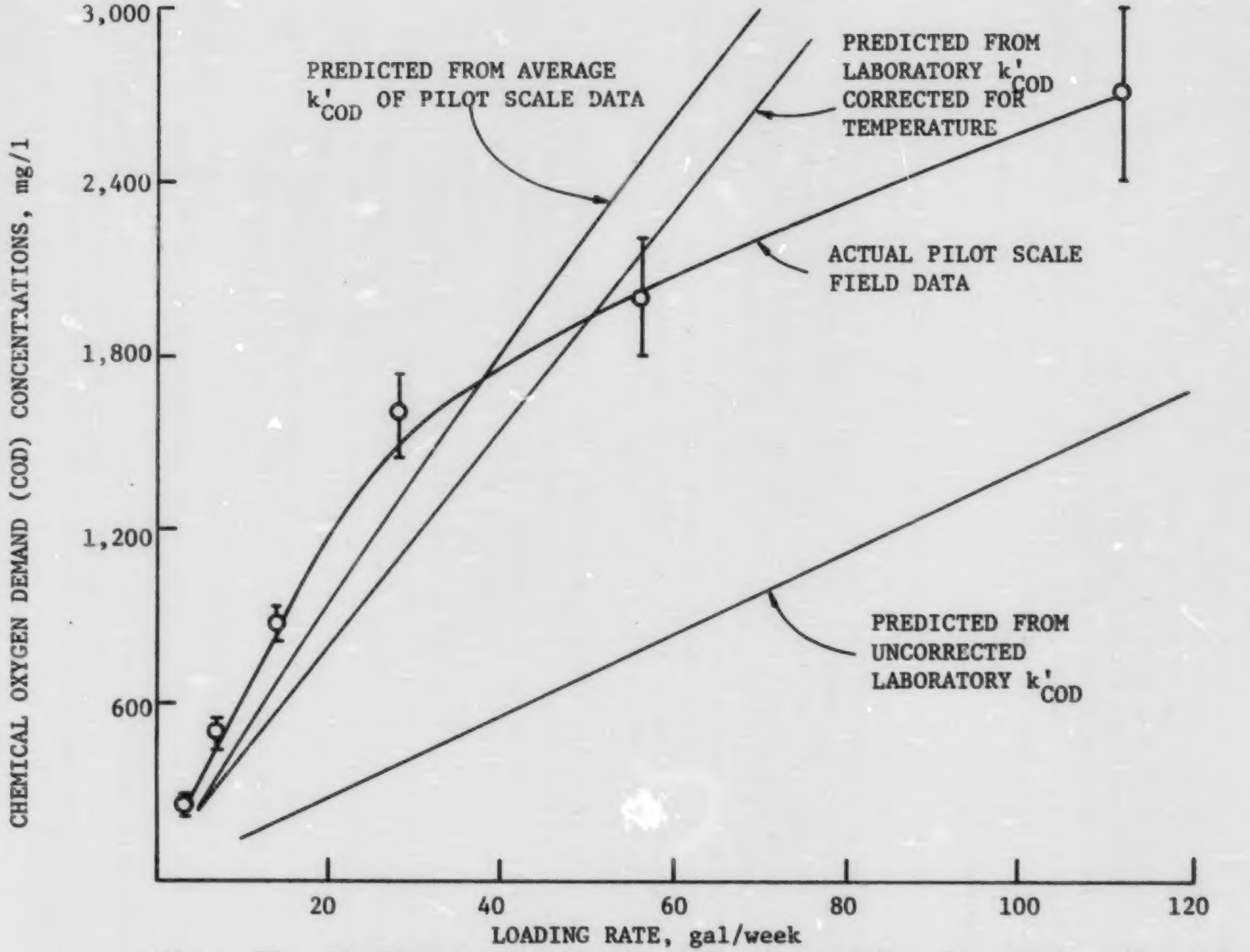


Figure 72. Steady-state supernatant COD concentrations for pilot-scale swine lagoons receiving various loading rates - experimental and predicted results (Equation 21).

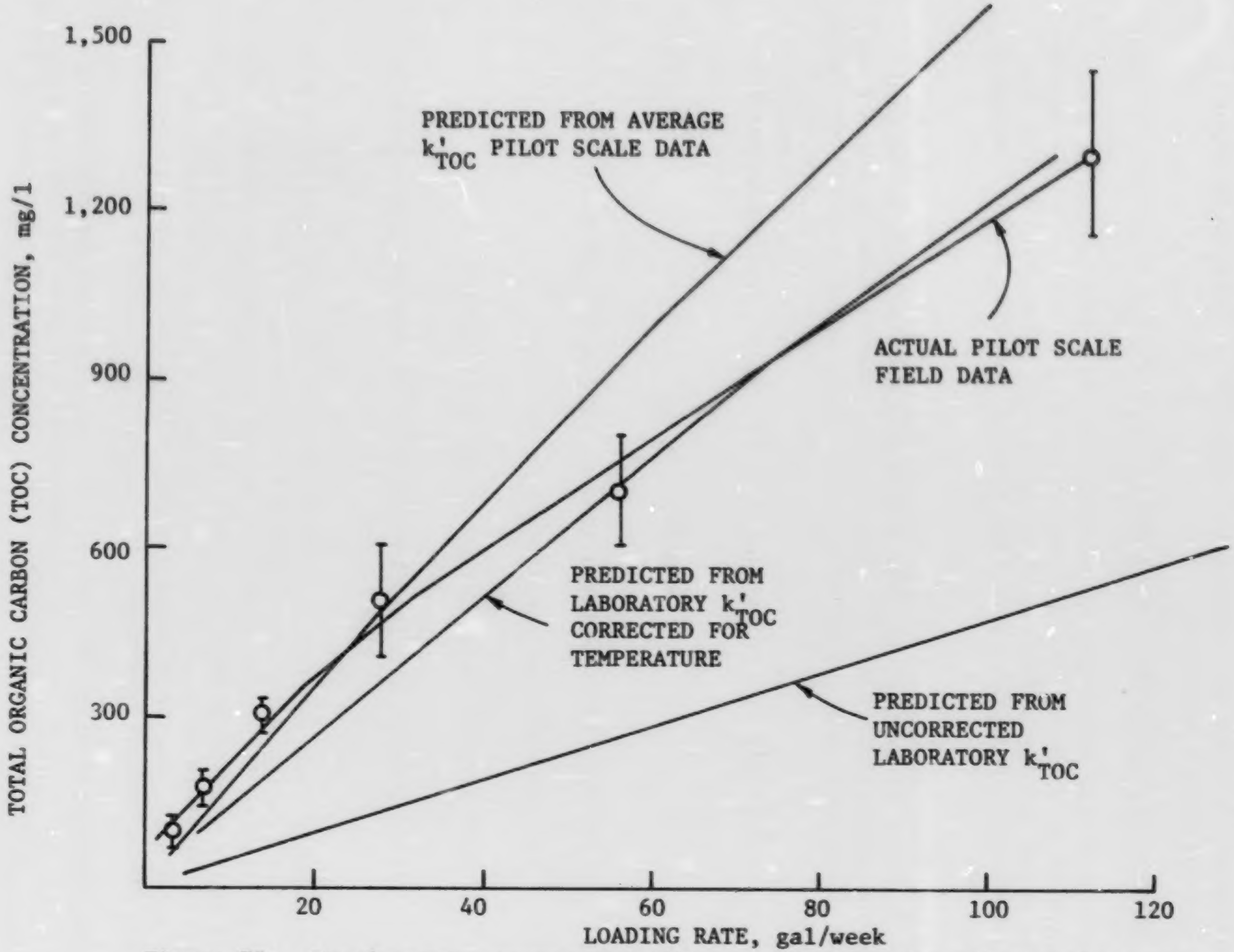


Figure 73. Steady-state supernatant TOC concentration for pilot-scale swine lagoons receiving various loading rates-experimental and predicted results (Equation 21).

compounds before total removal from the system as CO_2 may be an important reason. Despite these limitations, it should be possible with other waste types to do a single experiment at one loading rate and to then determine the supernatant response to changes in input waste concentration and rate.

CONTINUOUS LOADED APPROACH - NITROGEN

The same modeling mass balance approach was used with total Kjeldahl nitrogen as with the organic parameters (COD and TOC). The discussion of the batch loading model would be equally as valid and contain the same disadvantages as that described for COD and TOC, so that analysis was not redeveloped.

The major loss mechanism for nitrogen is surface volatilization of ammonia, which is assumed to obey the standard relationships derived for other ammonia solutions.[82] The rate of ammonia loss is proportional to the difference in gas phase and liquid phase concentrations when both are expressed on the same basis. This common basis is achieved by multiplying the gas phase concentration by the gas-liquid solubility coefficient (Henry's law coefficient). The volatilization expression then is:

$$R \approx (C_i - h_i P_i) \qquad (22)$$

where R = rate of volatilization, mg or g moles per hour

h_i = Henry's law coefficient, mg/l/atm

C_i = liquid concentration of species, i, mg/l

P_i = partial pressure of species i in the gas phase, atm

It was assumed that under most swine lagoon field conditions the gas phase concentration times the Henry's law constant was quite low so that the driving force for ammonia loss was approximately equal to the liquid phase concentration, C_i. This assumption was partially corroborated by field data of Miner[82]. Deviations from this assumption would generally lead to a lower rate of volatilization because the driving force would be lowered.

The expression for nitrogen loss was thus proportional to the driving force, C_i, and to the interfacial area between lagoon and atmosphere, A, so the overall mass balance yielded:

$$V \frac{dC_i}{dt} = QC_i^f - QC_i - b_i AC_i - \alpha QC_i^f \tag{23}$$

$$= QC_i^f \beta_i - QC_i - H_i C_i \tag{24}$$

where b_i = proportionally constant for ammonia volatilization, cm/week

A = surface area, cm^2

H_i = overall mass transfer coefficient, cm^3/week

The ammonia loss was also a first-order term with the rate of loss proportional to the concentration present in the supernatant and mathematically was comparable to Equation 12.

From a mechanistic approach there were several additional assumptions included in Equation 24. First, the parameter chosen to be modeled was total Kjeldahl nitrogen (TKN) instead of ammonia. While nitrogen losses from the lagoon system were primarily as ammonia, there were also gains or losses of ammonia which occurred by microbial breakdown of long chain molecules and deamination or incorporation into cell mass by synthesis. Thus, using ammonia would involve several other source and disappearance terms. Because the swine raw waste and lagoon supernatant contained a high fraction of ammonia and were uniform, it was assumed that anaerobic deamination and the mixing-diffusional process were not rate-limiting. The liquid to gas transfer of ammonia was assumed to be the rate-limiting step; hence, only the volatilization term was included in Equation 24. This assumption, although very reasonable for swine waste, warrants further verification when another waste type is involved.

Total Kjeldahl nitrogen losses represented predominantly ammonia losses so the use of either parameter would reflect total system losses. Volatilization of organic nitrogen compounds occurred but were insignificant when compared to volatilization of the smaller ammonia molecule. Conversions between organic and ammonia nitrogen would not appear as a TKN loss. Furthermore, it had been found that preservation of samples for ammonia analysis was much more difficult than for TKN, again because of microbial interconversions.[74] For these reasons the total Kjeldahl nitrogen was used to model nitrogen losses from anaerobic swine lagoons.

The supernatant TKN concentration derived from integrating Equation 24 was:

$$C_{TKN} = \frac{Q\beta C^f}{Q + H_{TKN}} - \frac{Q\beta C^f - (Q + H_{TKN})C^o_{TKN}}{Q + H_{TKN}} \exp\left[-(Q + H_{TKN})t/V\right] \quad (25)$$

The steady-state concentration was given by:

$$C^{ss}_{TKN} = \frac{Q\beta C^f}{Q + H_{TKN}} = \frac{Q\beta C^f}{Q + b_{TKN} \cdot A} \quad (26)$$

Steady-state results from the laboratory (14 l) and pilot-scale reactors were used to calculate the overall mass transfer coefficient H_{TKN} from Equation 26, Table 37. The overall transfer constant H_{TKN} was the product of the actual mass transfer coefficient, b_{TKN}, and the reactor surface area, A. Therefore, dividing H_{TKN} by the respective areas of laboratory and pilot-scale reactors yields the coefficient b_{TKN}, Table 37.

Table 37. MASS TRANSFER COEFFICIENTS FOR TOTAL KJELDAHL NITROGEN (TKN) AS LOST FROM ANAEROBIC SWINE LAGOON UNITS, EQUATION 26

Fraction of reference loading rate	Laboratory		Pilot Scale	
	H_{TKN} 1/week	b_{TKN} cm/week	H_{TKN} 1/week	b_{TKN} cm/week
1.0	2.8	5.2	520	5.5
.5	2.3	4.4	650	6.9
.25	1.9	3.5	690	7.3
.125			780	8.3
.0625			930	9.9
.031			1,060	11.2
Average		4.4		8.2

Predicted supernatant TKN concnetrations based upon uncorrected laboratory and average pilot-scale data for b_{TKN} are shown in Figure 74. Predicted values based upon uncorrected laboratory data were 30 to 50 percent above the measured values. Differences in temperature, wind conditions, and reactor size contributed to the deviations between measured and predicted values. The laboratory reactors had a sevenfold larger surface area to lagoon volume ratio than the pilot scale units and yet the mass transfer coefficients were fairly similar. The dependence of loading rate on nitrogen supernatant concentration for the pilot-scale field reactors more closely followed values predicted by field-scale data than predicted from uncorrected laboratory data, Figure 74.

The internal consistency of first-order TKN mass transfer coefficients was better than the first-order reaction constants found for COD and TOC. The k values for COD and TOC varied by a factor of three while the H_{TKN} varied by less than a factor of two over the same loading rate range, .031 to 1.0 times the reference rate. This consistency may be partially attributable to the physical mechanism for TKN removal (ammonia volatilization) as opposed to the microbially dependent loss of organics.

Analyses for COD and TOC verified that the reaction constant k_1 was much greater than the loading rate Q and thus predictive Equation 21 could be simplified because $k_1 >> Q$. However for TKN, the overall mass transfer coefficient H_{TKN} was of the same magnitude as Q so no further simplification was possible. Mechanistically, the relative magnitude of H_{TKN} and Q was related to lagoon response time. Writing the exponent part of the transient term (as done earlier in Equation 18 for COD and TOC) yielded:

$$\frac{Q}{V} + \frac{H_{TKN}}{V} = \frac{1}{T_r} + \frac{b_{TKN}A}{V} \qquad (27)$$

The second term, the inverse characteristic mass transfer time for total Kjeldahl nitrogen was the same magnitude as the inverse residence time. The inverse residence time as shown earlier in the COD discussion was relatively small. Thus, a slower supernatant TKN response to some change in the anaerobic swine lagoon operation such as increased input waste concentration would be expected. The discussion of the results for laboratory reactors and Imhoff cones pointed out that indeed a slower TKN response was observed as compared to COD and TOC.

Further examination of Equations 26 and 27 showed the relationships which exist among surface area, volume, and supernatant nitrogen concentration for swine lagoons. The response time, to achieve steady-state after an operational change, was affected by the volume, Equation 27, as the

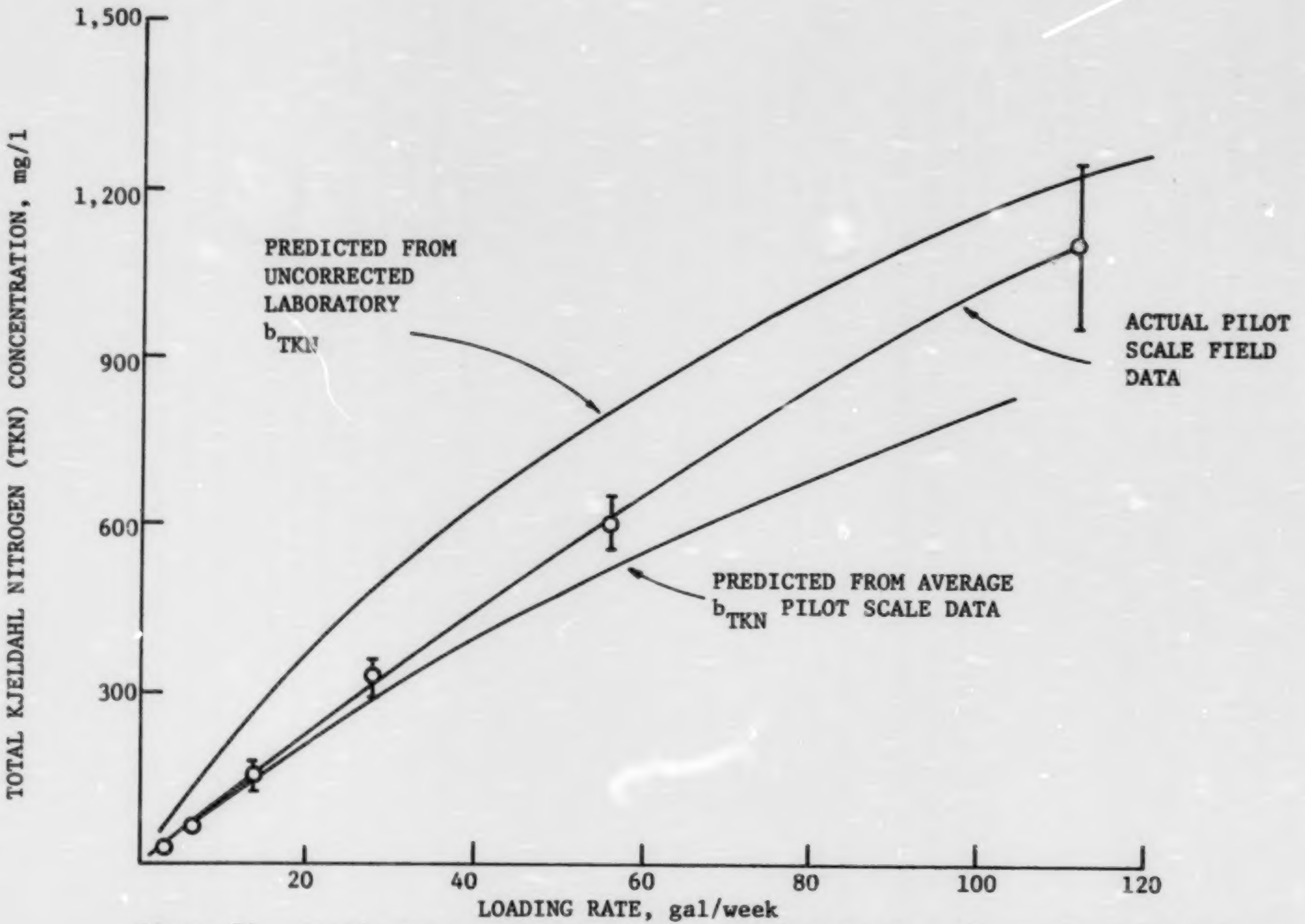


Figure 74. Steady-state supernatant TKN concentration for pilot-scale swine lagoons receiving various loading rates-experimental and predicted results (Equation 26)

ratio of surface area to volume. Thus, the larger the area to volume ratio, the faster the approach to steady-state conditions. The absolute value of the effluent nitrogen level, C^{ss}_{TKN}, was determined by the surface area, independent of volume, Equation 26. Larger surface area lead to lower supernatant TKN concentrations which indicated the surface volatilization mechanism as opposed to a bulk reaction removal. This areal removal dependence for TKN was contrasted to the microbial based volumetric dependence for COD and TOC, Equation 21.

In review, results of the continuous loading model for nitrogen appeared to give reasonable agreement to measured values when laboratory data or data from a single field unit were used to predict the effects of lagoon loading rate, climatological changes, and raw waste concentration. A few of the assumptions used in the model should be investigated further to provide a more precise predictive capability. The use of volatilization as the limiting step in conversion of organic nitrogen to ammonia which was lost from the system and the effect of loading rate on surface properties which may restrict volatilization should be reconsidered in future work.

SECTION VII

LAND APPLICATION STUDIES

EXPERIMENTAL PROCEDURES

Results of lagoon studies for swine waste indicated that while these reactors were efficient in terms of percent removal, effluent quality was not sufficient to allow stream discharge. Thus, lagoons must be considered as only pretreatment-storage units. The terminal process which provides for the most economically available achievement of the national goal of zero discharge for the animal production industry is the plant-soil receiver system.[83]

In order to evaluate the various facets of a lagoon pretreatment - land application system, a field-scale study was undertaken at the North Carolina State University Boar Testing facility described in detail earlier, Figure 75. The overall objectives were to investigate the effect of wastewater applications on crop quality, runoff potential, soil accumulation and soil-water migration, and to demonstrate the implementation of pretreatment - land application system for the swine industry.

Site Description

The total system included the Boar Testing Station buildings and a two-lagoon series. In order to reasonably obtain the full range of nitrogen applications desired, the effluent from the first-stage lagoon was used as the soil-applied liquid.

Prior to this study, the application site had been extensively used for forage crops. In May, 1972, the entire field was fumigated with methyl bromide. The field site sloped at a uniform 1-3 percent grade from the farm road toward the woods, an east-to-west orientation. Thus, the plots and monitoring devices were located in this direction. There was negligible north-south slope, thus limiting substantially the runoff and soil water flows to one direction, west to east. An interception drainline to cutoff soil water interflow from above the study site was installed at the 1- to 1.5-m depth. This line

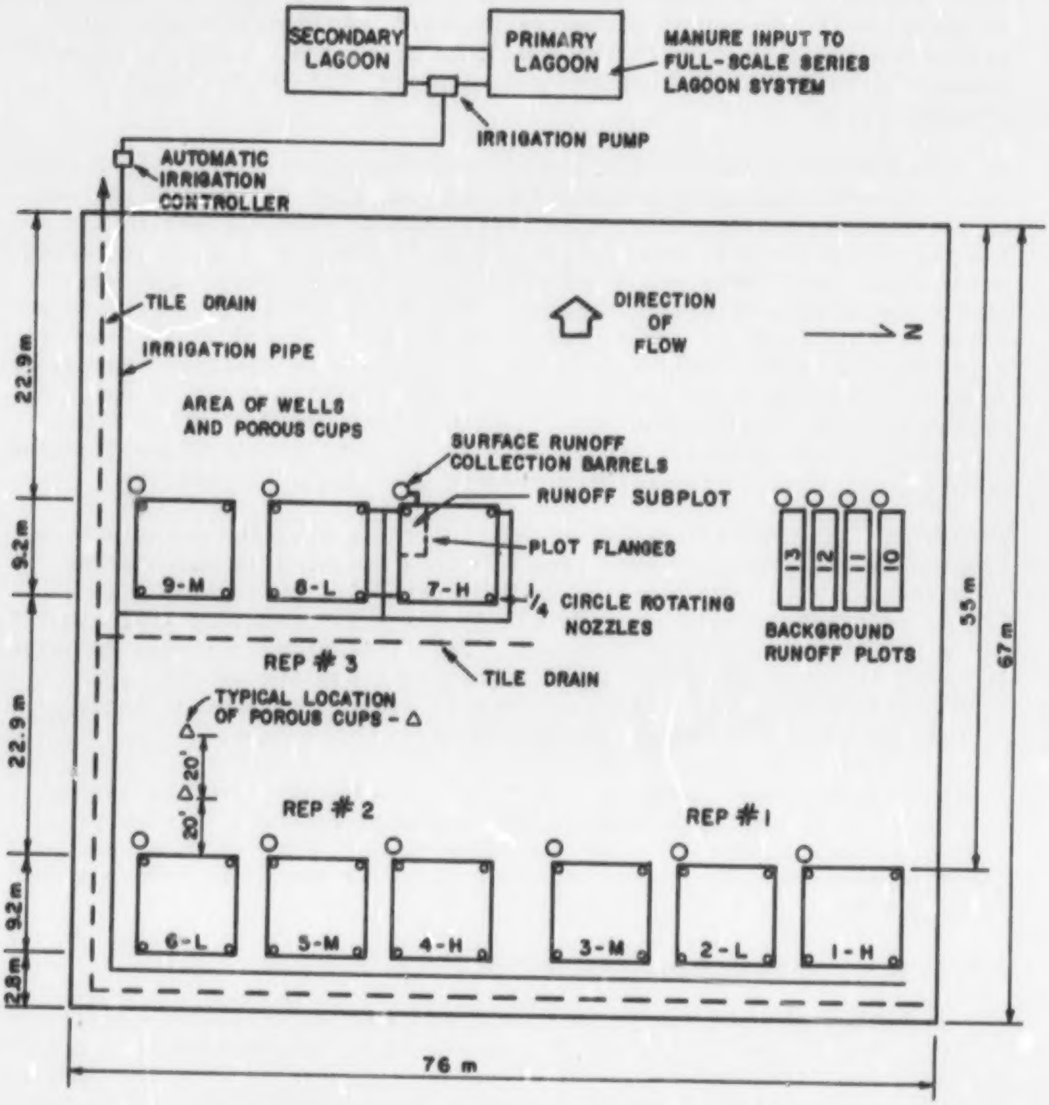

SECONDARY LAGOON
PRIMARY LAGOON
MANURE INPUT TO FULL-SCALE SERIES LAGOON SYSTEM
IRRIGATION PUMP
AUTOMATIC IRRIGATION CONTROLLER
TILE DRAIN
IRRIGATION PIPE
DIRECTION OF FLOW
N
AREA OF WELLS AND POROUS CUPS
SURFACE RUNOFF COLLECTION BARRELS
RUNOFF SUBPLOT
PLOT FLANGES
9-M
8-L
7-H
1/4 CIRCLE ROTATING NOZZLES
13
12
11
10
BACKGROUND RUNOFF PLOTS
REP # 3
TILE DRAIN
TYPICAL LOCATION OF POROUS CUPS - △
20'
20'
REP # 2
REP # 1
6-L
5-M
4-H
3-M
2-L
1-H
22.9m
9.2m
22.9m
9.2m
2.8m
55 m
67 m
76 m

Figure 75. Schematic diagram of facility developed to evaluate lagoon pretreatment - land application system for swine waste (Clayton).

sloped toward the southwest corner and then down the side of the study area, Figure 75. In order to divide the study area into two sections to increase the number of plots, an interception drainline was put across the field at 35 m in the downslope direction. Each drainline trench was back filled above the plastic drain tile with number 7 crushed stone.

An experimental plan was established to investigate three plot loading rates representing approximately 336,672, and 1,344 kg of nitrogen per ha. per growing season, with three replicates of each loading rate. Because all wastewater was irrigated from the same lagoon, these rates meant also that there was a 1:2:4 ratio of liquid volume applied with these different nitrogen rates. The field was divided into three areas or replicates of three plots each (plots 1, 2 and 3; 4, 5 and 6; 7, 8 and 9). Within each replicate, the plots were assigned loading rates on a random selection basis (1, 4 and 7 high rate; 3, 5 and 9 medium rate; 2, 6 and 8 low rate). Each 9.24- m by 9.24- m plot was isolated from surrounding area runoff by 23-cm wide galvanized flashing buried 13 cm deep giving a 10-cm above-ground isolation barrier.

To achieve uniform effluent distribution, the irrigation nozzles were located at the corner of each plot and were operated as one-quarter turn sprinklers having a radius equal to the plot dimension, 9.24 cm. The wetted area extended outside the 9.24-x 9.24-m area by approximately 0.6 m to assure total plot coverage. The irrigation cycle was adjusted so that the total amount of a given parameter applied to the 9.24-x 9.24-m area was equal to the experimental plan. The various application rates were achieved by varying the irrigation time.

Irrigation equipment included a 3. 8 cm main header from the lagoon, a 2 horsepower centrifugal pump (Stayrite DHHG), laterals to each plot, electric control valves to regulate flow to sprinkler nozzles, and a timer controller. The layout for each plot was identical and is shown in Figure 76.

Experiment and Monitoring Description

The experimental site was prepared and sprigged to certified Coastal Bermuda grass in the Spring of 1972 according to recommended practices. The area was irrigated as needed after sprigging and during the summer of 1972. A low rate of ammonium nitrate was applied after the sprigs began to produce new shoots and thereafter during the summer at approximately 30-day intervals. The experimental area had almost complete grass cover by fall and residue (10-15 cm) was left on the plots during the winter to reduce possible loss of stands from winter injury.

Application of swine effluent, consistent with the three loading rates based on nitrogen application, was initiated April, 1973, shortly after

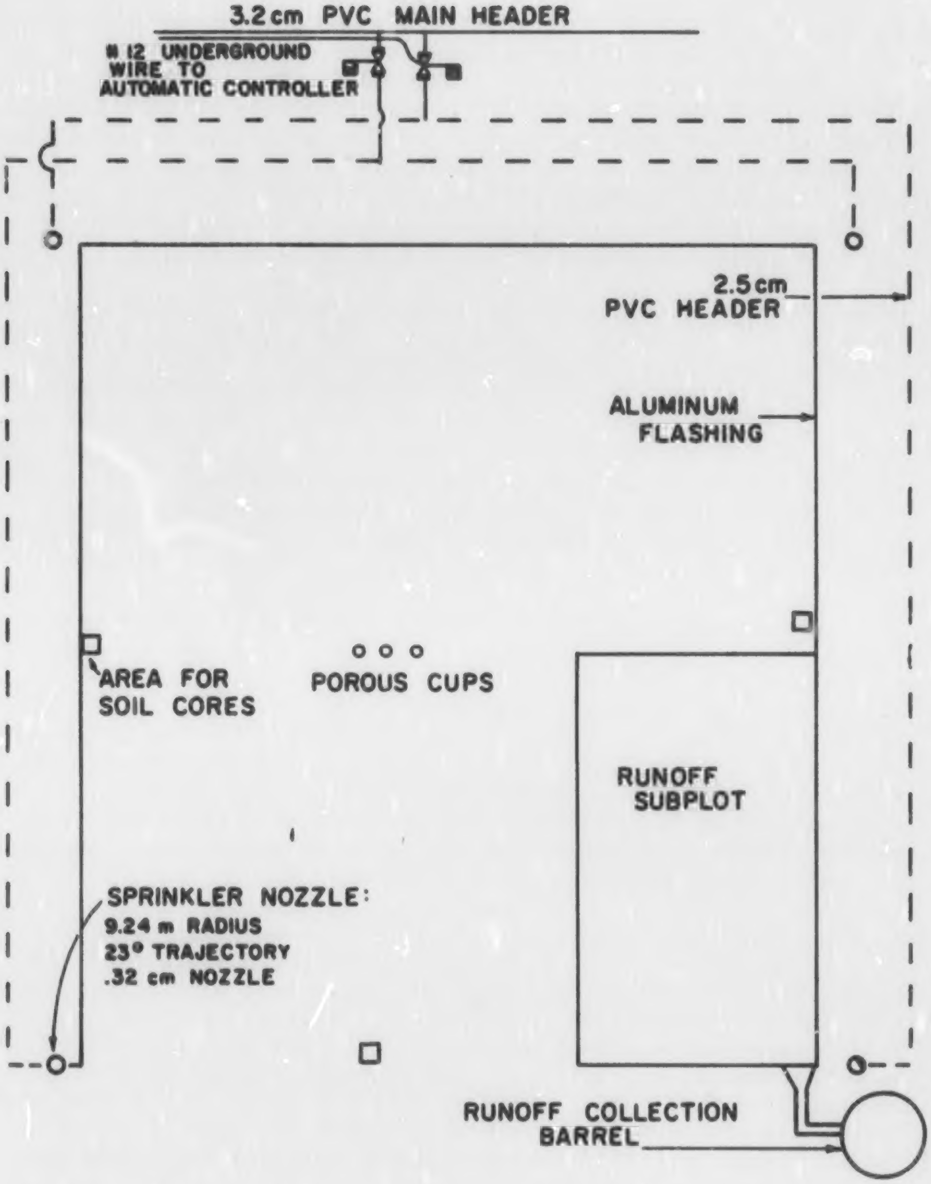

3.2 cm PVC MAIN HEADER
#12 UNDERGROUND WIRE TO AUTOMATIC CONTROLLER
2.5 cm PVC HEADER
ALUMINUM FLASHING
AREA FOR SOIL CORES
POROUS CUPS
RUNOFF SUBPLOT
SPRINKLER NOZZLE:
9.24 m RADIUS
23° TRAJECTORY
.32 cm NOZZLE
RUNOFF COLLECTION BARREL

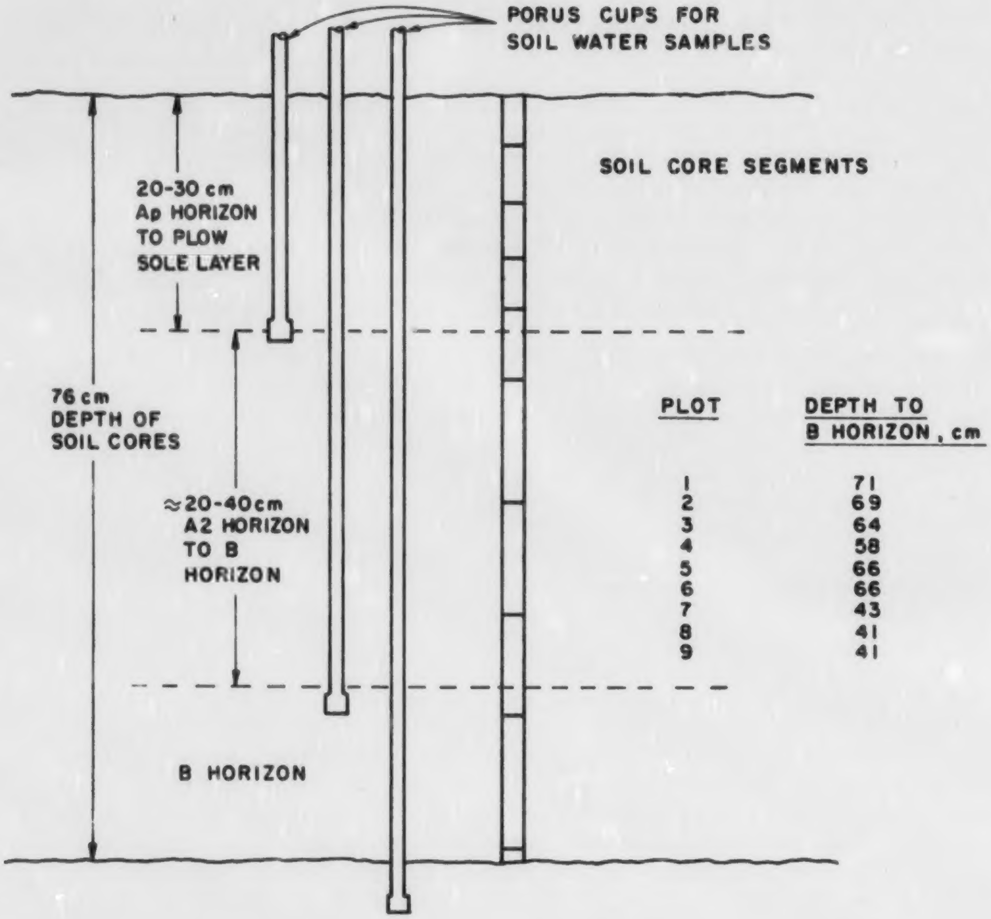
Figure 76. Schematic of experimental plots for land application of swine lagoon effluent.

the emergence of new growth. Irrigation was controlled by an automatic timer and was applied once every seven days on the same day of the week at night.

From the state maps and further testing, it was determined that the soil was a Norfolk sandy loam (Typic Palendult: fine-loamy, siliceous, thermic). This is characteristic of much of the Coastal Plains region of North Carolina and the Southeast. The profile contained an A horizon of loamy sand, with weak fine and medium granular structure material above the B horizon of sandy clay loam with a weak medium angular blocky structure, Figure 77. Hydrologically, this resulted in a well-drained or permeable layer (hydraulic conductivity, K = 6 - 9 cm/hr) on top of a tight or less permeable zone (K = 0.8 - 2 cm/hr) (Lutz[85]).

Soil water and movement of effluent constituents were monitored by sampling with 1 x 10^5 pascal ceramic cups. The sampling grid for each plot included one cluster of cups at the plot center and two at the downslope locations of 6.2 and 12.4 meters from the lower plot edge, Figure 75. A cluster consisted of cups at 23 cm (plow sole layer in A horizon); 56 - 71 cm for plots 1 through 6 and 30.5 - 46 cm for the slightly more eroded plots 7 to 9 (A-B horizon interface), and about 91 cm (25.5 cm below the surface of the B horizon), Figure 77. In addition to the in-place porous cups, three soil cores (1.6 cm diameter) were taken from each plot in the general area depicted in Figure 76. These were divided into 5-cm increments over the upper 25 cm and then into 10-cm increments until the 75-cm depth, Figure 77. Core holes were repacked with top soil and successive cores were taken up-slope of previous samples. Control cores to evaluate soil changes were taken in an area not receiving lagoon effluent about 23 m downslope from plots 2 and 3. This area was in Coastal Bermuda grass and received a very low level of ammonium nitrate for crop survival. Each week after irrigation the in-plot, soil-water cups were sampled. At locations outside the plot, sampling was more correlated with rainfall events because of sampling difficulty under unsaturated conditions. The soil cores were taken once every three months.

To evaluate irrigation losses and actual plot loading, samples were collected at the ground level with 7.5-cm diameter beakers (400 ml) for volume and constituent analysis. Two collectors were placed in each plot and then composited for analysis. Difficulty arose when rain fell between the start of an irrigation event and when the samples were composited. This happened infrequently and thus such samples were discarded. The amount of runoff from this type of plant-soil system was measured from a sub-area within the 9.24 m x 9.24 m study plot, Figure 76. This sub-area was 2.25 m wide and 4.5 m long and, of course, received the same effluent application as the rest of the plot. At the lower edge, a funnel and tubing arrangement channelled the runoff into a submerged 55-gal (208 l) drum. After each rainfall event,


PORUS CUPS FOR
SOIL WATER SAMPLES
SOIL CORE SEGMENTS
20-30 cm
Ap HORIZON
TO PLOW
SOLE LAYER
76 cm
DEPTH OF
SOIL CORES
≈20-40cm
A2 HORIZON
TO B
HORIZON
B HORIZON

PLOT	DEPTH TO B HORIZON, cm
1	71
2	69
3	64
4	58
5	66
6	66
7	43
8	41
9	41

Figure 77. Schematic of soil and water sampling profile in experimental plots for land application of swine lagoon effluent.

the total runoff volume was determined, a sample taken of the resulting liquid and the barrels pumped out with the liquid being dispersed just below the runoff plots as would be the case for the runoff.

Each set of three plots receiving a given effluent rate was harvested when forage reached the hay stage (30 - 35 cm of growth). Because the nitrogen applied was a variable, the forage grew at different rates for each treatment. Consequently, harvest dates varied with effluent application rates.

Two swaths (0.5 x 8.3 m) were harvested at random from the 9.24-m by 9.24-m plots with a Jari mower leaving a 5-cm stubble. The forage was weighed green and subsampled for dry matter and chemical determinations. The subsamples were dried in a forced air oven and dry matter yield was determined by multiplying green weight by the percentage dry matter and then expressed as dry matter per unit area (kg/ha). The dried samples were ground through a screen with 1-mm openings and stored in plastic bags until subjected to chemical analyses.

After sampling, the remaining forage from all replications of one treatment was clipped and tied into small, loose bales. These bales of fresh forage were placed into a bin type forced-draft dryer and held at 65° C until dry. Thereafter, the forage was rebaled into approximately 18-kg bales and stored in an open shed for later use in a feeding trial. Coastal Bermuda grass fertilized with 67 kg N/ha. of ammonia nitrate (no swine lagoon effluent) was harvested in midsummer at approximately the same height as the experimental plots, air cured, and designated as the control treatment.

Sample Collection and Analyses

Sampling in regard to plant and soil effects of effluent application to Coastal Bermuda grass consisted as follows: irrigated wastewater was collected at ground level within the plot during each effluent application in 400-ml beakers. All runoff resulting from effluent application or rainfall was funneled into a submerged 55-gal. (208 l) drum measured and samples taken for chemical analysis. Soil samples were taken in 15-cm increments prior to initiation of the experiment and every 3 months starting in September, 1973, in 5-cm increments to a 25-cm depth and every 10 cm from 25 to 75 cm. Soil water samples from one-bar ceramic cups were taken prior to effluent application and the day following the weekly application of effluent. Lack of soil moisture especially during late summer greatly limited the number of solution samples outside of plots and in plots where effluent was applied at low rates. Yield estimates of forage were obtained for each harvest and subsamples of forage were taken for dry matter and mineral determinations and nutritive evaluations. Effluent, soil, runoff, and soil water samples were frozen until analyzed. Forage samples were dried in a forced-air oven at 70° C and ground prior to analyses.

Effluent, runoff, soil water, soil, and forage samples were analyzed for total N, P, K, Ca, Mg, Na, Cl, and Cu. In addition, effluent was analyzed for COD, TOC, pH, NO_3, NH_3, Fe, Mn, and soils for pH, NO_3, NH_3, Fe, Zn, and Mn, and initially for exchangeable Al, organic matter, cation exchange capacity, percent clay; forage for Mn, Zn, and Fe; runoff for pH, COD, TOC, NH_3, and NO_3; and soil water samples for pH, TOC, NO_3, NH_3, and COD

After routine analysis for COD, TOC, pH, NO_3, and NH_3, several different methods of sample preparation were compared for analysis of runoff, effluent, and soil water samples. A large portion of the elements, especially in the effluent samples, were lost by filtering or centrifuging. Results from dry ashing of the samples also proved to be more variable than determinations carried out on the original sample after adequate dilution. Hence, all results of runoff, soil water, and effluent samples were from unaltered samples.

After extraction with water for Cl and NO_3 determinations, soil samples were air dried and extracted with 0.05 N HCl, 0.025 N H_2SO_4 for exchangeable K, Ca, Mg, Na, Cu, Fe, Mn, NH_3, and P. Soil pH was determined on a 1:1 soil-water ratio. After extraction with weak acid, an aliquot was taken for determination of NH_3 and the remaining liquid was dry ashed, concentrated HCl was added, redried, and resuspended with 0.5 N HCl. On all soil samples, N was determined by Kjeldahl; K and Na by flame photometer; Ca, Mg, Cu, Mn, Zn, and Fe by atomic absorption; Cl by a chlorimeter; NO_3 by direct scan on UV spectrophotometer, NH_3 by NH_3 electrode and P by a vanadate molybdate procedure. Forage samples were dry ashed, concentrated HCl added, redried and resuspended in 0.5 N HCl. Chemical analysis of forage after dry ashing were by the same precedures used for soil analysis. Liquid samples for soil water and runoff were analyzed according to procedures outlined for lagoon samples.

FIELD RESULTS AND DISCUSSION

The field equipment and monitoring system were installed to ascertain the feasibility of determining the significant pathways for swine lagoon wastewater in a plant-soil system. The resultant field data were used to establish a mass balance on these plots for several of the waste constituents. These data along with the soil profile characteristics and soil-water movement would be inputs into modeling systems and if successful could be utilized to determine environmental impacts of wastewater land application. The various mechanisms for removal or movement evaluated were crop uptake, surface runoff, soil accumulation, and soil-water interflow. Waste inputs were also delineated.

Irrigation Swine Lagoon Supernatant

The single-stage lagoon serving a Boar Testing facility with periodically varying total liveweight was the source of the wastewater irrigated. The first year of irrigation was late April through late September, 1973. Lagoon supernatant concentrations, hog populations, and complete facility description have been presented in the Farm-Scale Lagoon Portion of the Lagoon Studies and the Predictive and Interpretive Relationships Sections.

Calculation of the parameter which limits or determines the acres required per unit volume of lagoon effluent indicated that nitrogen was rate-limiting for this experiment. Nitrogen application generally limits the loading intensity for most animal waste in the moisture excess southeast, so the variable chosen for loading and replication in the test plots was nitrogen application rate. Nitrogen applications chosen were a) below minimum uptake of Coastal Bermuda grass, b) approximately equal to maximum uptake, and c) in large excess of crop uptake rates. These translated to 336, 672, and 1344 kg N/ha. over the seasonal growing period for North Carolina (May to September). There was no irrigation during the remainder of the year, thus these rates are 336, 672, and 1,344 kg N/ha./yr with first irrigation on April 20 and last on September 17, 1973.

The actual amounts of chemical constituents and water applied for each rate were as shown in Table 38 with each rate being replicated three times as different field plots. The actual amounts applied were slightly less than projected because of concentration variations due to lagoon changes and irrigation losses. However, the 1:2:4 ratio representing low, medium, and high was maintained. Actual applications were 300, 600, and 1,200 kg N/ha. Since the wastewater for application to all plots came from the same lagoon, the higher nitrogen rate plots also received higher water application. This farm utilized a dietary copper addition at about the 140-ppm level and thus the environmental impact of heavy metals in swine feed could be evaluated (Overcash[86]). However, the first stage lagoon reduced these metal levels so that the lagoon supernatant had a low copper and zinc concentration.

Experience from initial irrigation events was used to redirect the work plan. During the daytime period, the wind and resultant spray drift were significant so that actual plot application rates would be erratic. From experience with other irrigation systems, it was determined that late night or early morning application would result in less drift and thus the automated control system was programmed for this operation. The agreement between calculated volume of liquid needed to achieve weekly nitrogen loads and actual volume of liquid collected throughout the plots verified the superiority of night application.

Initially, the high nitrogen plots (1,200 kg N/ha./yr) were to receive one hour of application at the sprinkler nozzle rate of 1.25 cm/hr. Several

Table 38. CONCENTRATION AND AREAL LOADING RATE FOR SWINE LAGOON EFFLUENT REACHING PLOTS RECEIVING HIGH, MEDIUM, AND LOW RATES OF APPLICATION

Parameter	Average concentration mg/l	Application rate, kg/ha./yr		
		High	Medium	Low
COD	1,140	6,100	3,050	1,525
TOC	375	2,000	1,000	500
TKN	224	1,200	600	300
NH_3-N	148	800	400	200
P	49	270	135	70
K	220	1,200	600	300
Ca	52	280	140	70
Mg	62	340	170	85
Na	86	470	235	120
Cl	139	760	380	190
Cu	.49	2.7	1.35	.68
Zn	.56	3.0	1.50	.75
Mn	.41	2.2	1.1	.55
Fe	1.58	8.6	4.3	2.1
H_2O	--	55 cm/yr	28 cm/yr	14 cm/yr

attempts at this operation indicated that irrigation runoff occurred for this 2-3 percent sloped Coastal Plains soil. Therefore, this high level irrigation was reduced to two periods of thirty minutes spaced 2 to 3 hours apart. Wastewater irrigation runoff was reduced with this 30-minute, 1.25 cm per hour rate of application, but direct runoff occurred occasionally under wet conditions or when a sprinkler failed to rotate.

By comparing the concentration of lagoon supernatant prior to irrigation and that of the liquid falling onto the test plot surface, (collected in several 400-ml beakers and composited) the volatilization losses were determined, Table 39. However, these irrigation losses were only indicative of night application.

Table 39. COMPARISON OF IRRIGATED SWINE LAGOON EFFLUENT AND LIQUID REACHING PLOT SURFACE - NIGHT IRRIGATION

Parameter	Average concentration, mg/l		Percent loss
	Lagoon	Plot surface	
COD	1,274	1,140	11
TOC	387	375	3
TKN	269	224	17
NH_3-N	195	148	24

The irrigated liquid samples were collected on approximately the same day as the lagoon samples so the comparison of the two concentrations could be done directly. It was found that analytical errors for individual samples made the daily ratios of these two concentrations erratic. Therefore, averages for all dates with complete analyses (fifteen data points) were compared. It was felt that although there was some change in the lagoon supernatant concentration due to hog liveweight changes and operational fluctuations, this average was meaningful for detecting irrigation losses.

Comparison of lagoon supernatant concentrations and liquid concentrations reaching the plot grass level, Table 39, indicated that for the organic parameters, there was an approximately ten-percent drop in chemical oxygen demand but little or no change in total organic carbon. The concentration difference between lagoon supernatant and wastewater reaching the plot was significantly different from zero for COD (at the 95-percent confidence level) while the TOC difference was not significantly different (at the 90-percent confidence level). These facts would indicate that some oxidation of the wastewater occurred but little or no volatilization of organics. Ammonia, a more volatile compound, showed a greater concentration drop of approximately 50 mg/l from an initial level of about 270 mg/l. The total Kjeldahl nitrogen, containing organic and ammonia components, evidenced a similar 50 mg/l drop in concentration indicating that ammonia volatilization was the primary nitrogen loss mechanism. The TKN and NH_3-N concentration difference between the lagoon and plots was significantly different from zero at the 99-percent confidence. Thus, from a lagoon loaded at the reference rate approximately 25 percent of the nitrogen and 10 percent of the COD are lost during night irrigation. It should be emphasized that the sprinkler heads were small (9.2 meter radius: .32 cm nozzle) so the irrigation losses cannot be directly extrapolated to larger farm-type sprinklers. Higher losses would be anticipated for daytime irrigation because of higher temperatures and wind velocities.

Research at Maryland with poultry processing wastewater (Larson[87]) has shown that 5-10 percent of the ammonia falling on grass and soil surfaces is lost by volatilization. While these percentages would not be expected to hold for this waste, these facts do indicate potential additional volatilization losses beyond those measured for just irrigation.

The input to the plant-soil system could be expressed by two methods depending on the information available or needed by the designer. The first was to describe original lagoon liquid and the corresponding amounts of chemical constituents applied. This method would represent the parameters available to the designer of a land application system from lagoon sampling. The second method was based on the actual amounts of material reaching the plant-soil system. Application rates for both methods are given in Table 40. For purposes of mass balances, the second method was more useful; hence, the rates referred to in the discussion section are based on actual amounts reaching the plot surface. For purposes of the second method, irrigation can be viewed as an additional pretreatment resulting in material losses, Table 40.

Initial Soil Conditions

The preparation of the research plots and Coastal Bermuda grass cover is given in the land application experimental procedures section. Prior to application of swine lagoon effluent, soil cores were taken from all plots for detailed sectioning and analysis to determine baseline conditions. During the study additional cores were taken outside the application area and upslope from the plots to verify background soil concentrations.

Table 40. COMPARISON OF LAND APPLICATION RATE BASED ON LAGOON CONCENTRATION AND ACTUAL MATERIAL REACHING THE PLANT-SOIL SYSTEM

	High rate land application, kg/ha./hr	
Parameter	Lagoon basis	Field basis
COD	6,830	6,100
TOC	2,060	2,000
TKN	1,440	1,200
P	270	270

Initial conditions for the receiver plots were defined as the amount of the various constituents of interest found in the upper 75 centimeters of the soil profile. These amounts were expressed on a kilogram per hectare basis while the chemical analyses were obtained in kilogram of species per kilogram of soil. To convert between these measures, the plot area (97 m^2 = .0097 ha.) and the bulk density profile over the upper 75 cm of soil were needed. The bulk densities, Table 41, were the average of several core samplings and data indicated no abnormalities. A slightly higher density was found in the 20 to 36 cm zone which was the A2 zone. This density profile was then used with the concentrations (ppm) for all amount determinations in kg/ha. by means of standard calculations.

The background soil values were measured either from initial cores or subsequent control cores for nitrogen, phosphorus, potassium, calcium, magnesium, sodium, chloride, copper, zinc, iron, and manganese, Table 42. Comparison of the values for the upper 75 cm indicated a fair uniformity between the randomly selected plots for high, medium, and low application rates for parameters tested and thus indicated homogenity for all soil constituents. Differences were partly due to sampling and analytical variation. Complete data for individual plots and sampling dates are listed in Appendix C1. It was assumed that over the long term, the control cores would approximate initial conditions especially with respect to buildup of effluent applied constituents.

Table 41. BULK DENSITY VARIATION WITH DEPTH IN COASTAL PLAINS EXPERIMENTAL PLOTS (NORFOLK SANDY LOAM)

Depth, cm	Bulk density, g/cm^3
0-5	1.56
5-10	1.76
10-15	1.65
15-20	1.68
20-25	1.90
25-35	1.82
35-45	1.63
45-55	1.61
55-65	1.60
65-75	1.52

Table 42. AVERAGE INITIAL SOIL CONTENT IN UPPER 75 cm OF VARIOUS WASTE PARAMETERS FOR PLOTS RECEIVING HIGH, MEDIUM, AND LOW APPLICATION RATES

Parameter	Initial Concentration, ppm			Control plots
	High rate plots (1,4,7)	Medium rate plots (3,5,9)	Low rate plots (2,6,8)	Concentration, ppm
TKN	2,887	2,253	2,385	-
P	145	142	144	47
Ca	814	820	710	700
Mg	149	118	129	170
K	262	262	315	204
NO_3-N	-	-	-	4.0
Na	-	-	-	119
Cl	-	-	-	176
Cu	-	-	-	10.9
Zn	-	-	-	40
Mn	-	-	-	36
Fe	-	-	-	410

Plot Runoff

Rainfall Runoff Volume-

The impact of rainfall on the movement of waste constituents in the plant-soil system included rainfall-runoff, dilution, and soil percolation. The amount of waste material removed in runoff was measured from liquid volume and concentration measurements of the material collected in submerged barrels from 1/8 of the total plot, Figure 76. Runoff was found to occur as a result of rainfall as well as occasional effluent irrigation so these data were separated, Table 43 and 44. These preliminary runoff data represented fourteen events between start

Table 43. RAINFALL RUNOFF VOLUMES FROM EXPERIMENTAL PLOTS EVALUATED IN 1973

	Plot rainfall runoff, l/plot								
	High application plots			Medium application plots			Low application plots		
Date	1	4	7	3	5	9	2	6	8
4/27/73	495	248	1,748	278	131	1,095	1,166	52	994
5/4	45	--	--	--	--	64	--	--	--
5/18	75	15	64	38	--	45	109	--	60
5/21	709	765	1,095	652	221	780	776	128	919
5/29	1,163	1,178	1,725	983	649	1,380	1,316	315	1,609
6/18	79	38	45	38	105	191	56	--	191
6/25	1,598	1,714	1,721	1,391	1,185	1,875	1,553	143	1,721
7/16	1,174	724	1,406	435	165	911	330	19	1,084
7/30	844	608	761	293	75	623	559	86	1,058
9/19	979	1,174	1,744	671	1,035	1,665	671	221	863
11/30	120	101	--	--	79	49	150	94	--
12/10	--	8	--	34	56	--	79	--	--
12/20	75	45	60	34	53	41	98	--	--
Total	7,356	6,618	10,369	4,847	3,754	8,719	6,863	1,058	8,499

Table 44. EFFLUENT IRRIGATION RUNOFF VOLUMES FROM EXPERIMENTAL PLOTS EVALUATED IN 1973.

Date	Plot effluent irrigation runoff, l/plot								
	High application plots			Medium application plots			Low application plots		
	1	4	7	3	5	9	2	6	8
4/20/73	--	128	--	--	--	86	--	--	--
5/1	--	540	--	--	--	109	--	--	--
5/8	--	566	--	41	--	278	98	--	--
5/15	86	319	82	--	--	218	--	--	--
5/22	514	199	1,208	251	109	281	98	--	--
6/6	90	34	--	--	--	146	49	--	86
6/13	--	109	--	--	--	86	--	--	--
6/19	611	15	--	308	34	45	26	--	--
6/26	608	101	720	--	--	52	--	--	--
7/3	--	52	68	--	--	--	--	--	--
7/12	240	--	--	--	--	--	--	--	--
7/17	322	15	799	45	--	334	49	--	360
7/24	90	--	34	--	45	--	--	--	--
8/14	--	79	--	--	--	--	--	--	--
9/18	98	56	52	--	--	--	--	--	--
Total	2,659	2,213	2,963	645	188	1,635	319	--	446

up (5/73) through the end of waste application (9/73) and to the end of December, 1973. Comparing all plots, Table 43, there were only five storm events in which not every plot had some runoff.

Summation of all runoff volumes, scaled up by a factor of eight to be represented as total plot runoff, are also given in Tables 43 and 44. The extremely low volumes produced from plot 6 and to some extent, plot 5, opened questions as to the bias effect of these plots on the evaluation of material lost in rainfall-runoff. Possible explanations were inadequacy of liquid collection facilities or that the soil properties and crop conditions allowed greater infiltration. In any event, this entire replicate of plots (4,5,6) were eliminated from further calculations or conclusions pertaining to runoff. Results from these plots were, however, included in other aspects of this field study.

Rainfall-runoff relationships from these plot data should be taken as preliminary because the largest single event volume is 20 to 30 percent of the total runoff volume, Table 43, thus making determinations very error sensitive. Data should be taken over several years to obtain conclusive information. The third replicate (plots 7,8,9) periodically had greater runoff volume than the first replicate (plots 1,2,3) but within each replicate group there was about the same amounts of runoff even though each plot had a different nitrogen application and thus hydraulic load. Considering the soil profiles, Figure 77, the third replicate had 18 to 25 cm less topsoil above the less permeable B horizon; that is, it was more eroded. This reduced storage capacity would result in more runoff during large rainfall events thus leading to slightly higher total runoff volumes. However, despite such limitations, there appeared to be a degree of uniformity among the other loading rate replicate (plots 1, 2, 3) and thus some definable trends became apparent. Comparisons between plots receiving animal waste and plots under normal pasture conditions or in other types of land use should be made to better relate these data to baseline runoff from predominantly rural areas.

For the first (1,2,3) and third replicates (7,8,9) the plot receiving the higher loading had the highest and rather similar runoff volume. Increase runoff especially immediately following irrigation for the high rate plots (1,200 kg N/ha./yr) due to wetter conditions could explain recorded runoff volume differences. Rainfall data was not available to correlate storm intensity or volume to runoff volume for so few events. Averaging the runoff volume for the two replicates used over the period shown in Table 43 yielded 8,100 l per plot. Rainfall over this period from a farm weather station 1.25 Km from the site was 51,800 l per plot for a runoff percentage of approximately 15 percent.

Irrigation Runoff Volume-

Runoff occured as a result of irrigation events on some occasions for even the low waste loading plots, Table 44. Again, eliminating replicate 2 (plots 4, 5, and 6) the average irrigation runoffs were calculated. A more pronounced dependence on liquid loading rate was evidenced for irrigation related runoff than for rainfall runoff with the highest irrigation runoff occurring at the 1,200 kg N/ha./yr application rate. The runoff as a percentage of the applied liquid was 4.3 percent, 3.7 percent, and 1.5 percent for 1,200, 600, and 300 kg N/ha./yr, respectively. The liquid application rate was 1.3 cm per hour with varying duration irrigation used to give the required nitrogen rates. This irrigation runoff although small compared to the total applied, was significant compared to rainfall runoff especially for the high nitrogen rate plots. The expected high concentration of pollutants in this liquid emphasized the need to preclude this type of runoff. However, continued long-term monitoring may show that these runoff volumes become significantly reduced as the received plot matures.

Some of the irrigation runoff seemed directly related to prior rainfall. Runoffs from the high waste plots on 5/22 and 6/26 were quite large compared to other events and on 5/21 and 6/25 there were heavy rainfalls as evidenced by the large rainfall runoff. On 6/18, there was a light rainfall-runoff event and the irrigation runoff was correspondingly lower on 6/19. At lower waste application rates, the link between prior rainfall and irrigation runoff was less conclusive than at the high rates. Certainly, irrigation immediately after rainfall events will require more control if runoff is to be minimized. Also a buffer distance to allow infiltration of irrigated area runoff would reduce the impact of the irrigation runoff found for the application conditions of this study.

Waste Constituent in Runoff-

Analysis of samples taken from the runoff barrels was performed for a wide variety of constituents. However, experimental difficulties prevented analysis of all samples, thus a complete assessment of the amount of material lost from the plots by means of runoff was not made. Chemical oxygen demand was the parameter analyzed most consistently. Using the subplot area and runoff volumes for the 8 samples collected representing 60 percent - 70 percent of the total runoff volume, the kg/ha.of COD lost was calculated for the two replicates of the three loading rates, Table 45. Although there was a slightly greater runoff volume for the high nitrogen plots, the liquid concentration of organics (COD) lost could not be directly correlated to waste application rate, Table 45. Neither the high nor low rate plots consistently yielded the greatest amount of COD runoff. Again 30 percent - 50 percent of the total COD was lost during the largest individual runoff event so that normal errors could easily have distorted runoff evaluations for this single year of data. The COD applied was 6,100, 3,050,

TABLE 45. CONCENTRATION OF RAINFALL RUNOFF FROM EXPERIMENTAL PLOTS RECEIVING SWINE LAGOON EFFLUENT.

Date	Parameter	Parameter concentration, mg/ℓ								
		High application plots			Medium application plots			Low application plots		
		1	4	7	3	5	9	2	6	8
5/8	COD	116	108	105	136	No runoff	116	101	No runoff	128
	TKN	9	-	7	13	"	-	-	"	8
	NO_3-N	4	6	-	-	"	-	-	"	-
5/21	COD	35	39	109	27	39	113	117	43	101
	TKN	2	-	2	2	6	3	6	-	3
	NO_3-N	.3	-	1	0	0	.55	.45	0	.70
	Ca	2.2	2.7	1.5	1.7	3.3	2.1	2.4	1.7	1.1
	Mg	.86	.98	.71	.69	25.0	.95	.83	.66	.47
	K	4.8	4.7	5.2	5.8	10.7	5.9	21	5.3	4.7
	Na	5.5	5.5	9.9	5.5	2.3	7.7	8.3	1.1	6.6
	Cu	.011	.033	-	.011	.011	.011	.044	-	.022
5/29	COD	61	49	34	68	91	106.5	38	152	148
	TKN	6	3	2	6	4	6	.5	10	11
	NO_3-N	.20	0	0	0	.1	.6	.03	.15	.55
	o-PO_4-P	2	2	1	1	1	1	.12	2	3
	Ca	3	2.7	2.0	2.3	1.9	1.3	5.3	3.0	1.3
	Mg	1.33	1.05	.96	.87	.82	.67	1.82	1.03	.63
	K	6.8	18.6	6.7	4.8	17.7	8.8	8.8	14.0	8.4
	Na	1.1	7.7	1.7	6.6	1.3	1.5	3.1	9.9	2.2
	Cu	.011	.033	.022	.011	.022	.033	.132	.022	.022
6/18	COD	176	111	123	188	84	84	100	No runoff	84
	TOC	32	32	30	62	32	25	20	"	25
	TKN	21	9.5	11	13	16	7	6	"	6
	NO_3-N	8	6	11	9	5	2	6	"	3
	o-PO_4-P	5.5	9	3	5	3	3	2	"	2.5
6/25	COD	34.5	19.5	27	31	27	4	27	35	12
	TOC	10	5.5	5	5	5	5	5	5	5
	TKN	2.5	2	2	2	2	2	2	2.5	1
	NO_3-N	1	.5	1	2	1	1	2	1.5	1
	o-PO_4-P	3	3	1	1	.9	.9	.7	.1	.4
7/16	COD	39	39	31	39	54.5	35	58	117	27
	TOC	10	10	11	10	30	10	25	10	9
	TKN	2.5	2.5	4	3	15	4	7	4	3
	NO_3-N	1	3	2	3	6	1	3	7	1
	o-PO_4-P	9	8	8	6	8	3	3	3	3
7/17	COD	298	96	27	169	No runoff	21	117	No runoff	35
	TOC	195	65	20	90	"	18	73	"	24.5
	TKN	25	15	11	12	"	5	8	"	11
	NO_3-N	5	5	2	15	"	1	4	"	1.5
	Ca	23.7	13.3	9.3	9.7	"	4.2	9.3	"	4.1
	Mg	5	4.16	4.0	3.6	"	2.2	3.5	"	2.2
	K	107	64.9	16.8	26.3	"	12	38.5	"	13.2
	Na	26.4	10.5	.0	24.2	"	1.5	13.9	"	2.2
	Cu	.34	.10	.099	.24	"	.099	.088	"	.077
7/30	COD	100	39	31	35	73	54	73	324	58
	TOC	40	12	17	14	23	15	32	57	14
	TKN	5	4	3	2	6	5.4	6	11	3
	NO_3-N	1	3	3	2	10	2	2	13	1
	o-PO_4P									
	Ca	9.9	7.1	7.0	6.5	7.9	21.3	5.5	7.1	2.9
	Mg	3.4	2.9	3.0	2.3	3.0	2.4	2	2.6	1.1
	K	22.2	19.5	12.4	12.5	30.8	11.0	23.1	25.0	9.9
	Na	4.6	2.4	1.2	1.9	6.2	2.0	2.3	4.4	.66
	Cu	.29	.11	.077	0	.08	.11	.099	.10	.11
11/30	COD	-	105	No runoff	No runoff	70	31	-	70	No runoff
	TOC	-	25	"	"	25	40	-	25	"
	TKN	-	19	"	"	5	4	-	5	"
	NO_3-N	-	54	"	"	10	21	-	10	"
	o-PO_4-P	-	3	"	"	0	0	-	0	"
7/24	Ca	29.3	No runoff	30.2	No runoff	18.4	No runoff	No runoff	No runoff	No runoff
	Mg	5.1	"	4.5	"	4.5	"	"	"	"
	K	215.6	"	204.6	"	61.6	"	"	"	"
	Na	58.3	"	55	"	15.4	"	"	"	"
	Cu	.143	"	.594	"	.154	"	"	"	"
8/14	Ca	No runoff	25	No runoff	No runoff	No runoff	"	"	"	"
	Mg	"	4.9	"	"	"	"	"	"	"
	K	"	177	"	"	"	"	"	"	"
	Na	"	45	"	"	"	"	"	"	"
	Cu	"	.24	"	"	"	"	"	"	"

and 1,525 kg/ha. for the high, medium and low rate plots, respectively, so that the percentage lost in runoff decreased with increasing loading rate from 2 percent to .5 percent.

The rainfall runoff concentrations for the remainder of the parameters evaluated were included in Table 45. Conclusions based on the measured amount of material lost in runoff were not made; instead trends were deduced from concentration values and only approximate order of magnitude values for runoff losses were determined.

For the four events listed as receiving complete analysis, Table 45, there appeared to be uniformity of concentration values for a single event with differences in concentration between rainfall events. This similarity of concentration would imply (as with the COD) that there was little differences among loading rate and that the amount lost as a percentage of that applied decreased with increasing loading rate. This uniformity of runoff amount was only a preliminary trend based on approximate concentration and volume values. Further data over a number of years will be needed for conclusive results. Order of magnitude calculations for rough average runoff concentration values and total runoff volumes indicated that less than five percent of applied constituents appeared in the rainfall runoff.

Runoff from irrigation events was analysed for two dates, 7/24/73 and 8/14/73, Table 45. The concentrations for the majority of the parameters was roughly 50 percent to 80 percent of the irrigated liquid concentration. Observations of the irrigation runoff from the remainder of the plot showed that within 0.3-1.5 m the liquid has soaked into the soil. Therefore, it was concluded that the impact of irrigation runoff would be insignificant for this type of plant soil system provided a small buffer strip was utilized.

Crop Uptake and Utilization

Dry Matter Yield-

The Coastal Bermudagrass was managed as a hay crop with the plots for each loading rate harvested at the 30-35 cm height, detailed in the Land Application Experimental Procedures Section. Evaluation of data uniformity indicated that the second replicate (plot 4, 5, and 6) was not significantly different from the first and third replicates. The second replicate, while not used in runoff determinations, was included in crop uptake calculations. Dry matter yields and percentage dry matter for the three high, three medium, and three low rate plots were determined, Table 46.

Table 46. DRY MATTER YIELDS (kg/ha.) AND PERCENTAGE DRY MATTER OF COASTAL BERMUDA GRASS FOR FIRST-YEAR APPLICATION OF THREE LOADING RATES OF SWINE LAGOON EFFLUENT (1973)

Loading rate	Harvest date	Dry matter yield average of 3 replicates (kg/ha.)		Percentage dry matter
Low	6/13	1.955		27.9
	7/16	3,212		30.9
	8/16	3,865		39.2
	9/21	2,257		30.7
Total		11,290	Mean	32.2
Medium	6/13	2,125		22.5
	7/11	4,308		25.4
	8/7	2,747		22.7
	9/10	4,525		30.5
	Residue after frost	900		84.2
Total		14,605	Mean without residue	25.37
High	6/13	2,393		22.2
	7/6	3,392		22.9
	8/1	3,773		23.3
	8/31	4,623		28.7
	Residue after frost	1,970		69.9
Total		16,151	Mean without residue	24.3

The dry matter contents were lower at the 600 and 1,200 kg N/ha./yr rates than for the 300 kg N/ha./yr rate demonstrating the greater water uptake and top growth associated with excess nitrogen conditions (Doss[88]). The residue samples were high in dry matter because they were taken after autumn frosts but low in yield and thus were used only to determine total parameter amounts removed. Comparison of the dry matter yield among the three effluent treatments demonstrated increased growth with increased effluent loading rate. However, only the dry matter yield difference between the 300 and 600 kg N/ha/yr rates and 300 and 1,200 kg N/ha./yr rates were significant ($P \leq .05$). The use of 1,200 kg N/ha./yr did not significantly increase dry matter yield over the 600 kg N/ha. rate indicating the plateau region for response to nitrogen. The amount of N, P, (Woodhouse[89]) and K (Woodhouse[90]) applied at the highest effluent application rate was more than double the amounts found to produce maximum yield of Coastal Bermuda grass in North Carolina.

Weekly observations of grass growth and appearance did not evidence any adverse effects for any of the experimental plots. The only visible forage symptom was a temporary chlorotic condition at the high rate application which developed in the regrowth during September, 1973. Foliar analysis indicated no nutrient abnormalities and no permanent damage occurred with the loading rates used. Thus, the crop yields reflected response under good growing conditions.

Nutrient and Trace Mineral Uptake-

Analysis results for each grass harvest is presented in Tables 47 and 48 on a dry matter basis. These were the first year results and conclusions represented initial trends. In general, the increase in grass dry matter concentration of the elements tested was significant between the various effluent application rates. Zinc represented the exception to the trend of increased concentration with increased loading rate. However, using the incremental increase between the application of 300 and 600 kg N/ha./yr as a reference, further increases in plant composition commensurate with the increase from 600 to 1,200 kg N/ha./yr were found only for calcium, manganese, and iron. The other parameters increased only slightly with increased effluent application. Reasons for the first year information showing larger Ca, Mn, and Fe increases at the high rate were not fully defined but may have involved initial soil deficiencies or alterations in soil exchange capacity with varying water content or pH conditions.

Conversion of the plot yields and grass composition to the amount of material removed by the crop was completed and shown in Table 49. Increased effluent application resulted in increased crop removal since both yield and concentration increased with loading rate. However, for none of the parameters did the removal as a percentage of the applied material increase with larger waste input, Table 49.

Table 47. MINERAL CONCENTRATIONS OF COASTAL BERMUDA GRASS (AVERAGE OF THREE REPLICATIONS) FOR FIRST-YEAR APPLICATION OF THREE LOADING RATES OF SWINE LAGOON EFFLUENT (1973)

Loading rate	Harvest date	N	P	K	Ca	Mg	Cl
		% D.M					
Low	6/13	2.07	0.190	1.81	0.34	0.18	0.763
	7/16	1.54	0.175	1.66	0.27	0.15	0.697
	8/16	1.81	0.177	2.06	0.25	0.15	0.833
	9/21	1.92	0.183	1.84	0.28	0.17	0.823
	Mean	1.84	0.180	1.84	0.29	0.16	0.778
Medium	6/13	2.21	0.203	2.14	0.32	0.20	0.887
	7/11	2.21	0.227	2.43	0.38	0.22	0.867
	8/7	2.71	0.243	2.41	0.39	0.23	0.793
	9/10	2.09	0.193	2.28	0.35	0.24	0.970
	Mean	2.31	0.215a	2.32	0.36	0.22	0.878
High	6/13	2.46	0.207	2.41	0.38	0.21	0.883
	7/6	2.75	0.227	2.72	0.43	0.24	0.717
	8/1	2.90	0.243	2.64	0.50	0.28	0.663
	8/31	2.50	0.217	2.47	0.46	0.29	0.627
	Mean	2.65	0.225a	2.56	0.44	0.26	0.722

Means with same letter are not significantly different at a 95-percent confidence level.

Table 48. MINERAL CONCENTRATIONS OF COASTAL BERMUDA GRASS (AVERAGE OF THREE REPLICATIONS) FOR FIRST-YEAR APPLICATION OF THREE LOADING RATES OF SWINE LAGOON EFFLUENT (1973)

Loading rate	Harvest date	Na	Cu	Mn	Zn	Fe
		ppm				
Low	6/13	910	11.67	57.0	24.0	262.3
	7/16	1055	11.00	44.0	23.0	202.3
	8/16	840	10.00	38.0	24.6	097.6
	9/21	955	10.33	38.3	25.3	112.3
	Mean	940	10.75	44.3	24.2a	168.7
Medium	6/13	1200	13.33	64.0	25.3	377.0
	7/11	1800	17.00	59.6	26.0	283.7
	8/7	1780	15.00	59.0	26.6	236.3
	9/10	1750	13.00	45.0	21.6	119.3
	Mean	1640	14.58a	56.9	24.9a,b	254.0a
High	6/13	1400	18.00	69.0	26.6	370.3
	7/6	1410	15.66	73.0	24.3	287.3
	8/1	1910	16.66	84.3	30.0	249.6
	8/31	1610	12.00	64.3	24.6	132.3
	Mean	1580	15.58a	72.65	26.4b	259.4a

Means with same letter are not significantly different at 95-percent confidence level.

Table 49. CROP REMOVAL RATES FOR FIRST YEAR OF SWINE LAGOON EFFLUENT APPLICATION TO COASTAL BERMUDA GRASS (1973)

Parameter	Crop uptake, kg/ha			Crop uptake percentage of applied		
	Low rate	Medium rate	High rate	Low rate	Medium rate	High rate
TKN	207	336	428	70	57	36
P	20	31	36	30	23	13
K	201	340	413	69	56	34
Ca	32.5	52.5	71.2	46	37	25
Mg	18.5	32.7	41.6	22	20	12
Na	10.6	23.9	25.6	10	10	5
Cl	88	128	116	46	33	15
Cu	.12	.21	.25	18	16	9
Zn	.27	.36	.42	34	25	14
Mn	.50	.83	1.18	90	82	55
S	22.2	28.8	33.6	--	--	--
Fe	1.9	3.7	4.1	89	87	48

Hay Quality and Animal Acceptability-

Coastal Bermuda grass from the plots receiving swine lagoon effluent and control plots receiving only ammonium nitrate were used to assess Coastal Bermuda grass quality as an animal feed. Grass preparation was described in the Land Application Experimental Procedures Section. Hay quality was evaluated with the two-stage Tilley and Terry *in vitro* procedure and the Kjeldahl nitrogen analysis as an expression of crude protein content. The former technique estimated the *in vivo* dry matter digestibility of forages by means of in *in vitro* dry matter disappearance (IVDMD) under controlled conditions

Average IVDMD (four harvest dates) were about 57 percent to 58 percent of initial dry matter and were quite similar for the high, medium and low application rates, Table 50, with the greatest differences occurring in harvest-to-harvest measurements. For comparison, the control was 46 percent IVDMD while standard forage values for Alfalfa were 49 percent IVDMD (50 percent *in vivo*) and bromegrass 67 percent IVDMD (62 percent *in vivo*). Thus compared to the Bermuda grass grown under standard fertilizer conditions and alfalfa grass, the IVDMD for the crop from the effluent plots was 7 percent to 12 percent higher.

The total N (TN) concentrations for these forages increased with effluent nitrogen loading rate. However, the fact that at even the high rate, the total nitrogen was less than three percent was unexpected compared to forage values of up to five percent obtained under greenhouse conditions (Burton[91]). As expected, the correlations of IVDMD and TN were positive and highly significant (Table 50) for the low and medium rate plots. At higher rate, there was a lower correlation level possibly because of other limiting factors besides nitrogen.

Crop yields for individual harvests were insufficient for hay intake trials so composite samples were made, i.e., for the low, medium, and high rates, grass was mixed together from 7/16 and 8/16, 7/11 and 8/7, and 7/6 and 8/1, respectively. Thus, the four forage sources, ground through a 3.8-cm screen in a Davis mill, available for feeding, were a) control (inorganicly fertilized forage), b) low rate of effluent, c) medium rate of effluent and d) high rate of effluent.

Sheep were chosen for hay acceptability testing because sufficient forage was not produced for cattle feeding. Based on previous work in the Animal Science Department, it was felt that if sheep would consume the field hay then acceptability by cattle would be assured. A total of 16 ewes (8 Dorset, 8 grade Suffolk) were weighed, placed in individual pens and fed control hay *ad libitum* for an 11-day standardization period.

Two animals refused to eat and were removed from the experiment. After the animals were accustomed to the Bermuda grass hay, they were randomly assigned, within breed groups, to the four hay treatments. Hays were fed ad libitum for a 13-day experimental period. Hay intake was determined from pounds of hay offered minus pounds of weighback. Samples of each hay were obtained daily throughout the experimental period. These samples were composited and analyzed for crude protein (percent total N x 6.25) and dry matter.

Table 50. IN VITRO DRY MATTER DISAPPEARANCE (IVDMD) AND TOTAL NITROGEN CONCENTRATION OF COASTAL BERMUDA GRASS HAYS FOR FIRST-YEAR APPLICATION OF THREE LOADING RATES OF SWINE LAGOON EFFLUENT, 1973, (MEAN VALUES OF 3 REPLICATIONS)

Loading rate	Harvest date	IVDMD (%)	Total N (%)	Correlation (r) between total N and IVDMD
Low	6/13	58.9	2.07	0.89
	7/16	51.6	1.54	
	8/16	58.7	1.81	
	9/21	58.3	1.92	
	Mean	56.9	1.84	
Medium	6/13	55.7	2.21	0.98
	7/11	55.0	2.21	
	8/7	61.4	2.71	
	9/10	55.0	2.09	
	Mean	56.8	2.31	
High	6/13	53.4	2.46	0.58
	7/6	63.2	2.75	
	8/1	58.5	2.90	
	8/31	58.3	2.50	
	Mean	58.4	2.65	

There was no evidence of reduced hay palatability due to the use of lagoon effluent during crop production when compared to the control, Table 51. The hay intake per unit body weight was not significantly different among the loading rates studies, Table 51, although the crude protein content increased with increased loading. Within the animal types the grade Suffolk lines consumed more hay in relation to body weight than Dorset ewes, .02 versus 0.15 kg hay/kg body weight ($P<.05$). These trends in palatability, crude protein level, hay composition, and animal roughage intake by breed and forage species found in the first year study need to be continued for further optimization of crop utilization. Long-term effects of lagoon effluent irrigation on hay quality must also be considered.

Table 51. ANIMAL INTAKE AND HAY COMPOSITION FOR COASTAL BERMUDA GRASS FOR FIRST-YEAR APPLICATION OF SWINE LAGOON EFFLUENT, 1973.

Loading rate	No. of ewes	Hay intake		Hay composition, %		
					Crude protein	
		kg per head	kg per kg body weight	Dry matter	As feed	Dry Basis
Low	3	1.21	.018	91.9	10.2	11.1
Medium	3	1.35	.017	92.2	13.8	15.0
High	4	1.27	.016	92.4	17.0	18.6
Control	4	1.34	.018	91.7	8.2	8.9

Soil Accumulation

The soil buildup after one year of swine lagoon effluent application was evaluated from analyses of soil cores taken of the top 75 cm of the soil solum. These cores were sectioned to provide profile as well as the total 75 cm core data. Three cores were taken from each plot and composited at each depth prior to analysis as outlined in the Land Application Procedure Section. All subsequent core samples have been taken in the same general vicinity but upslope to eliminate any leaching effects associated with the refilled holes. The check or control cores were taken in triplicate downslope from plots 2 and 3 at a distance equivalent to the upslope edge of plots 7, 8, and 9, Figure 75. The region of the control cores had an established stand of Coastal Bermuda grass and received maintenance level fertilization.

Initial soil cores were taken at 15-cm increments because the upper 12-15-cm was plowed prior to the experiment and thus assumed to be uniform. Later samples were taken at 5-cm segments until the 25-cm depth and then 10-cm segments to the 75-cm depth. Thus, soil profile comparisons were not one-to-one. The difference was most prevalent in the surface area where concentrations changed the most; hence concentration profile comparisons were approximate. However, this difference in sampling procedure did not affect overall determinations in the upper 75 cm of these plots.

A large number of pathways or mechanisms for removal or attenuation of the applied waste constituents exist in the field situation. The three most significant pathways in this study were movement or loss associated with lateral or vertical soil water flows, uptake by the growing crop, and the incorporation of chemical constituents into the soil matrix. This latter mechanism represented accumulation or buildup in the experimental situation. If the rate of buildup was greater than loss rates to percolation or crop uptake, there would be a positive accumulation; if the rate of buildup was less, there would be a negative accumulation or a soil depletion.

Materials such as potassium or calcium which accumulate in a soil system are retained with varying binding energy levels. Traditional definitions refer to three reservoirs, listed according to decreasing binding energy as 1) tightly bound in the lattice of secondary minerals, 2) moderately held as at the outer edges of the clay lattice, and 3) that in soil solution or retained by the soil exchange capacity. Heavy or extended wastewater applications could cause components to enter any of these reservoirs and thus accumulate. As the energy required to remove these compounds or elements decreases, the likelihood of detecting them with the tests employed in this study increases. Temperature, soil water levels, and microbial populations can also influence the concentration of an element as these factors alter the amount of exchangeable material (Murrmann[92]; Hunt[93]). Other elements such as chlorides evidence little accumulation in soils similar to those of this study because of the low soil anion exchange capacity.

Thus the amount of soil accumulation was affected by the particular element or compound, the ability to detect all of a material present, and the levels present prior to the initiation of the swine lagoon effluent study. The presence of these complexities in determining parameter soil levels required some simplfying assumptions. Primarily, it was assumed that for each increment of a material added in the effluent regardless of loading rate, approximately the same fraction of the amount accumulating in the soil was detected by chemical analyses. Also over several years of application, it was assumed that the build-up of materials determined from the soil core analyses would better approximate the actual soil conditions. The first year data would thus be observed for trends.

Concentration data for the initial cores; those taken from effluent plots in September, 1973, after one season of irrigation; those taken from the same plots after three more months with no waste input, December, 1973; and September and December, 1973, cores from control areas were tabulated in Appendix C1. Extensive comparisons of these data showed that results for plots 4, 5, and 6 (removed from discussion of runoff data) were not significantly different from the first and third replicates, and hence, were included in further discussions. From these nine sets of data, averages for plots receiving the same waste load were made to that the results appeared as high, medium, and low rates corresponding to the three plots receiving 1,200, 600, and 300 kg N/ha./yr, respectively.

The soil concentration in September and the accumulation over the first irrigation season in the upper 75 centimeters of soil, expressed as kg per ha. for the waste constituents analyzed were listed in Table 52. Nitrogen data indicated the Kjeldahl nitrogen level increased at the high rate as did the nitrate nitrogen levels. For the medium and low rates, there were slight increases in nitrate levels over the control areas, but little TKN accumulation. The other major nutrients, P and K, showed increases at the high rate (28 and 174 kg/ha., respectively) but evidenced only slight accumulations and depletions at the medium and low rates.

Cations Mg and Na were determined to have increased slightly in the upper 76 cm of soil while Ca levels decreased even at the high rate. Other micro nutrients and heavy metals varied in the levels of accumulation or depletion, Table 52.

These data presented a mixed picture with respect to soil accumulation in the entire upper 75 cm of soil. In general, the higher rates plots had higher accumulated levels of the applied waste constituents while there was little difference between loading rates for some parameters.

The soil levels and accumulation over the initial soil conditions for the cores taken three months after irrigation termination in December, 1973, were tabulated in Table 53. Comparison of September and December data indicated the potential variability in these large average values for the upper soil zone, since some levels such as TKN show as increase after this three-month time period. Despite the absolute soil level disparities recorded for the December, 1973, and September, 1973, data the trend of higher accumulation at the higher application rates was evident for both samples.

Table 52. SOIL ACCUMULATION IN UPPER 75 cm BENEATH PLOTS RECEIVING SWINE LAGOON EFFLUENT AFTER ONE SEASON, SEPTEMBER, 1973

Parameter	Soil concentration, kg/ha			Increase in soil amount between initial or control plot conditions and September conditions, kg/ha		
	High rate	Medium rate	Low rate	High rate	Medium rate	Low rate
TKN	3,063	2,265	2,374	176	11.2	-11.2
P	174	140	109	28	-2.3	-37
K	436	306	218	174	43.7	-96.3
Ca	768	796	652	-45.9	-23.5	-58.2
Mg	222	179	140	72.8	61.6	11.2
Cl	603	510	492	427	334	316
Na	130	138	81.8	11.2	19.0	-37.0
Zn	28.7	29.0	21.3	-11.2	-11.2	-19.0
Cu	17.7	25.5	14.3	6.83	14.7	3.47
Fe	298	319	291	-113	-91.8	-120
Mn	43.9	46.8	64.1	8.06	11.0	28.2
NO_3	81.6	12.2	12.9	77.3	8.18	8.85

Table 53. SOIL ACCUMULATION IN UPPER 75 cm BENEATH PLOTS RECEIVING SWINE LAGOON EFFLUENT AFTER ONE SEASON, DECEMBER, 1973

Parameter	Soil concentration, kg/ha			Increase in soil amount between initial or control plot conditions and December conditions, kg/ha		
	High rate	Medium rate	Low rate	High rate	Medium rate	Low rate
N	3,189	2,811	2,866	301	558	480
P	255	177	131	110	34.7	-13.4
K	716	642	325	454	380	10.1
Ca	736	790	766	-78.4	-30.2	56
Mg	162	160	143	13.4	42.6	14.6
Cl	393	388	358	217	212	183
Na	237	174	168	119	54.9	47.0
Zn	37.0	28.2	28.3	-3.36	-12.1	12.0
Cu	18.9	10.9	12.8	8.06	0	1.90
Fe	556	486	496	144	75.0	85.1
Mn	48.0	50.5	53.3	12.2	14.7	17.5
NO_3	21.4	10.4	7.17	17.4	6.38	3.14

Calcium, chloride, and nitrates showed consistent decreases in the total amounts present between September and December. All of the waste constituents were expected a priori, to decrease during this three-month dormant period when only rainfall leaching was occurring. However, there was only 7.5 cm of rainfall during these three months which was only about 30 percent of the expected normal. However, some parameters still appeared to increase possibly representing variability in this testing procedure.

Treating September and December data as two estimates of soil buildup and averaging the data the conclusion that greater accumulation occurred at the heavy loading rate remained valid. The variability in amount of material accumulated per unit area prohibited exact determinations of buildup rates after a single season of application.

More detailed data analyses indicated some of the reasons for this large, short-term variability. One or two incorrect analyses or contamination of one or two bottom segments could represent 20 percent to 30 percent of the total parameter quantity. Additionally, for several components, the amount applied at the medium and low rates was small compared to the initial amount in the soil, e.g., Ca, P, Mg and N. Of more importance for many of the parameters such as K and Fe was the high levels of primary and secondary minerals in the soil. These were often thousands of kilograms per hectar as compared to levels evidenced in analyses in the order of hundreds of kg/ha. Thus, small shifts in available levels of these minerals would have introduced data variability.

Soil profile analyses of chemical constituents were more useful in observing initial trends because surface effects could be identified and erroneous points more easily elucidated. These data were averages of values in Appendix C3 for replicated plots receiving the same waste input applications, high, medium or low. Only the profiles for high, low, and either initial or control cores were plotted to demonstrate differences associated with loading rates.

Total Kjeldahl nitrogen levels did evidence a large increase at the surface zone commensurate with the amount of nitrogen added, Figure 78. By March, 1974, the concentration profile was about the same as in September, 1973 at irrigation termination except for a modest nitrogen decrease in the upper 5-cm zone. Soil nitrate from oxidation of applied TKN was evident for the higher loading rates throughout the waste application profile in comparison with the control cores, Figure 79. Decreases in the soil profile nitrate levels between September and December, 1973, probably represented leaching losses. Nitrate levels were a very small percentage of the TKN detected.

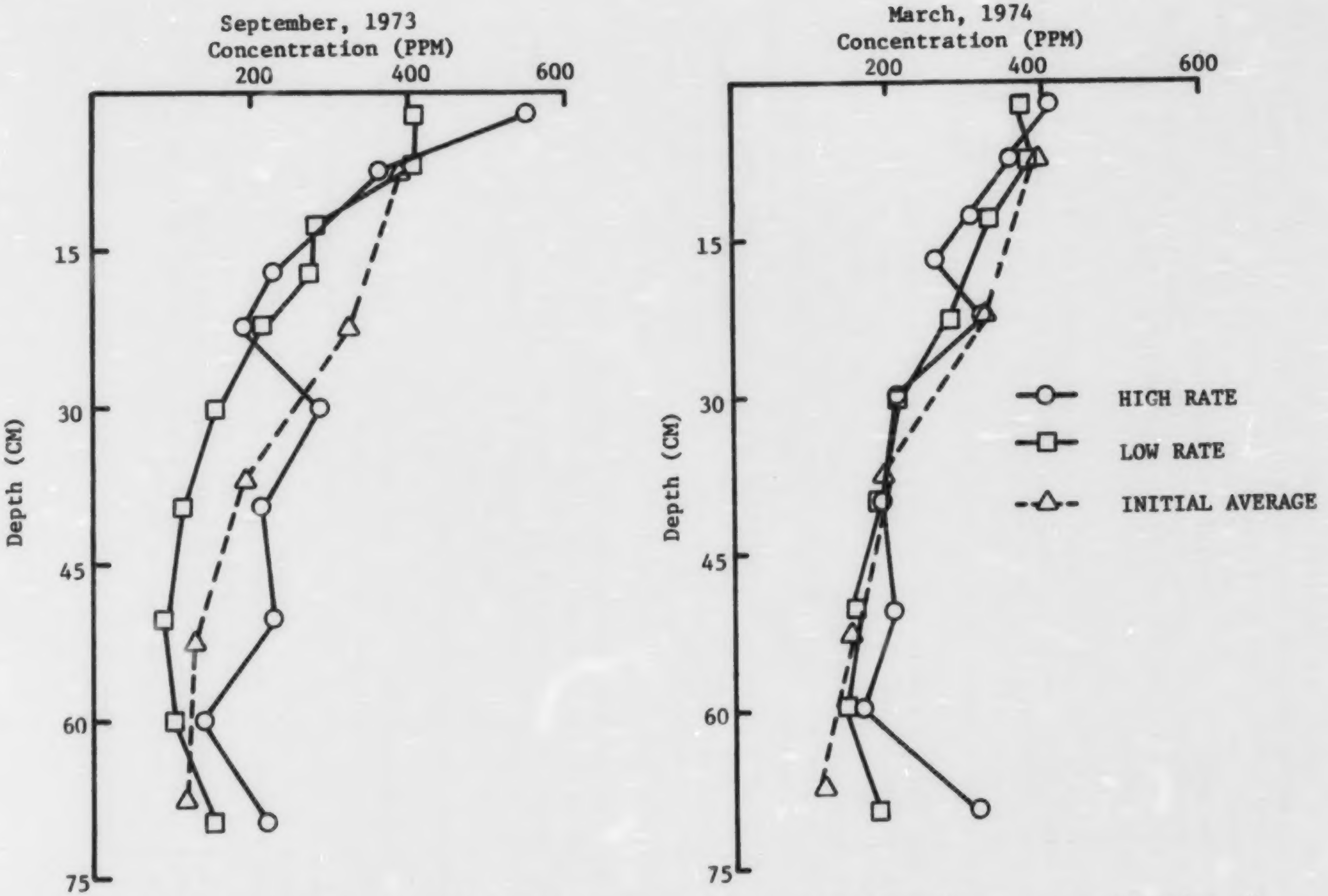


Figure 78. Soil profile total Kjeldahl nitrogen concentrations for first-year application of swine lagoon effluent, 1973, at 1200 and 300 kg N/ha.

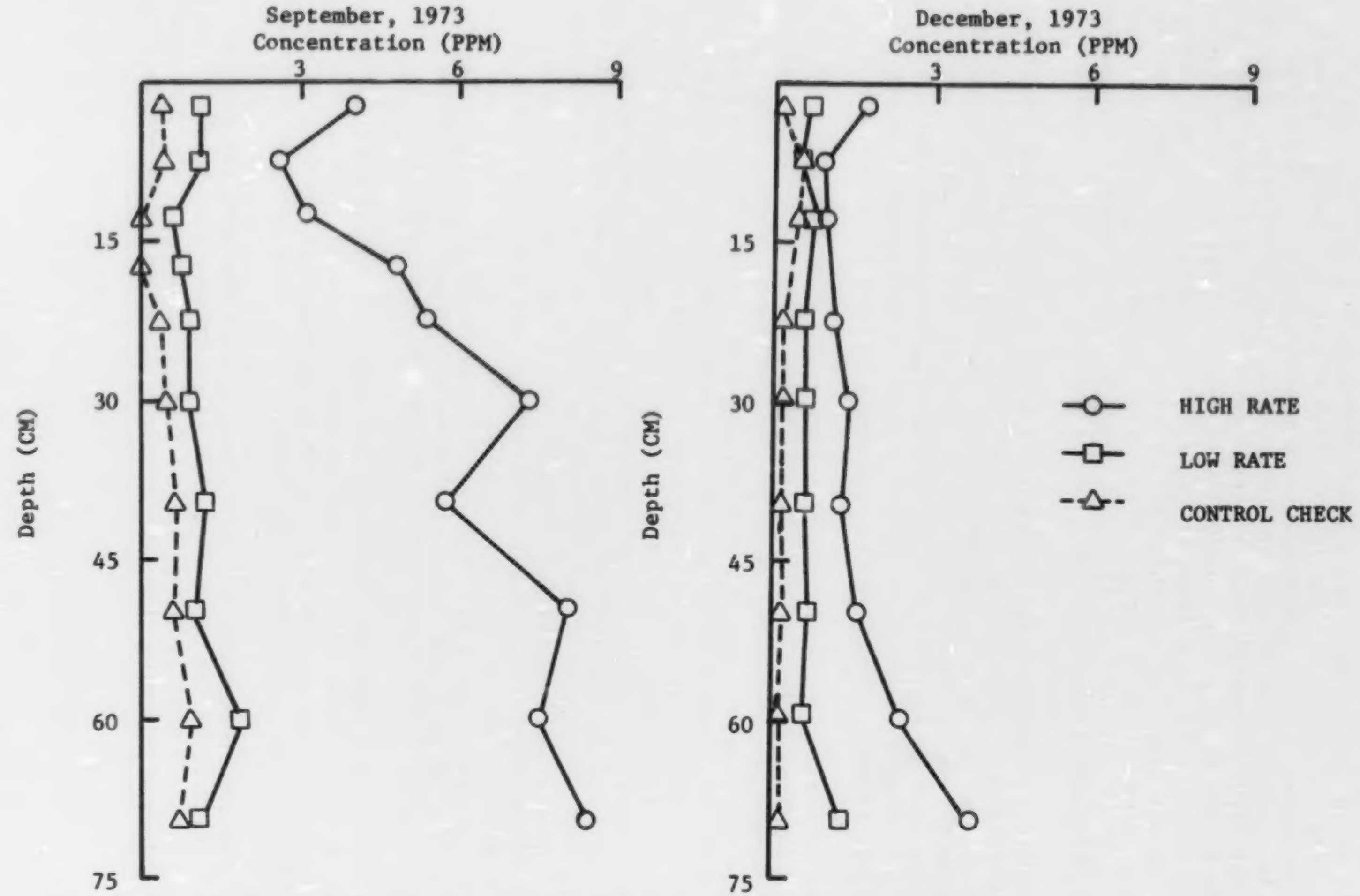


Figure 79. Soil profile nitrate concentrations for first-year application of swine lagoon Effluent, 1973, at 1200 and 300 kg N/ha.

Soil calcium concentrations remained relatively constant from before application through one season (both September and December, 1973, profiles) of loading for the low and high application rates, Figure 80. The September control sample evidenced a lower surface zone concentration possibly due to crop uptake in this unirrigated area. Magnesium, another divalent cation, was increased for both the low and high effluent plots in the surface zones by September, 1973, Figure 81. Cores taken in December, 1973, were lower in magnesium concentration at the surface but low and high rate concentrations were still somewhat above control levels below the 75-cm depth. This trend of downward leaching was found for both the low and high rate plots and thus by December, 1973, surface concentrations returned to levels existing prior to waste irrigation.

Phosphorus, largely removed from the raw waste by the lagoon treatment mechanisms described earlier, was found to accumulate mostly for the high rate of application and then basically in the surface zones, Figure 82. Between September and December, there was a slight increase in the surface zone concentration of phosphorus indicating analytical variations. As with calcium, the control area was lower in phosphorus than the original samples presumably due to Coastal Bermuda grass growth.

Three monovalent and more mobile ions were measured through the upper 75-cm profile, K, Na, and Cl. Potassium was increased over the initial soil levels throughout the whole profile for the high rate, Figure 83. At the low rate, no significant increases were found. The profiles for both low and high rates had similar potassium concentrations at the 0- to 5-cm depth with the low rate soil levels decreasing to background levels at about 20-cm. The high rate remained elevated over background down to the 75-cm depth. These data indicate that the exchange capacity was satisfied for the surface layer even at the low application rate after which downward movement resulted. The December soil potassium profile was higher than September for the high rate plots. Explanations for this increase were not totally available but the effect of season on exchangeable levels of K has been reported.[94] The low rate plots showed the anticipated leaching loss of K to lower soil layers, Figure 83, as evidenced by the lower surface concentrations and slightly higher levels in the lower profile for the December data.

The soil sodium profiles were about the same or slightly elevated over control cores, Figure 84, for low and high application rates. Sodium in the control cores, the low rate plots and the high application plots for December was above levels measured from the same areas in September.

Chloride soil concentrations were approximately the same for the low and high plots in the upper 36 cm and above control core levels, Figure 85. The heavy application plots had greater chloride levels from the 36- to 75-cm depth indicating that some movement out of the upper soil profile

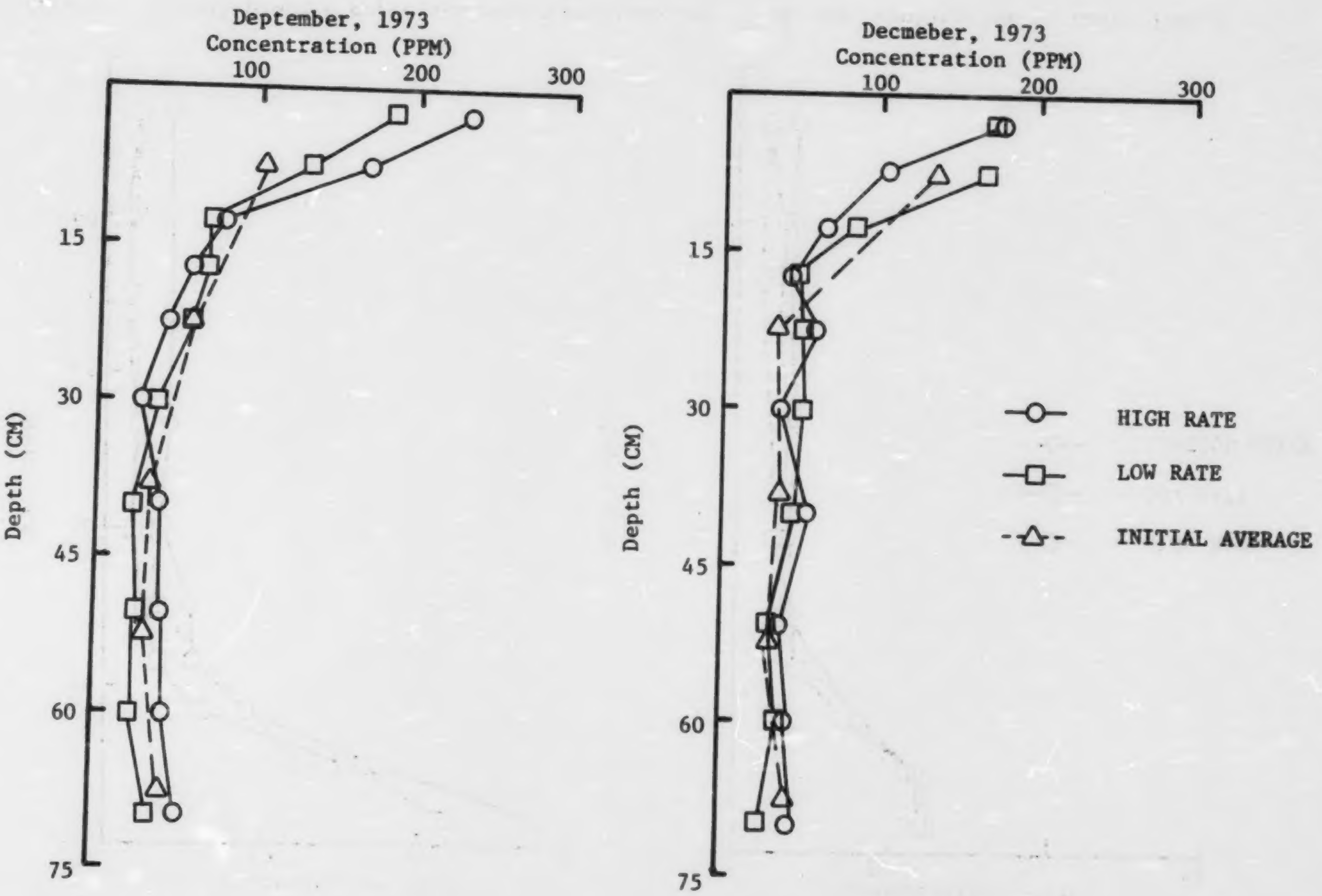


Figure 80. Soil profile calcium concentrations for first-year application of swine lagoon effluent, 1973, at 1200 and 300 kg N/ha.

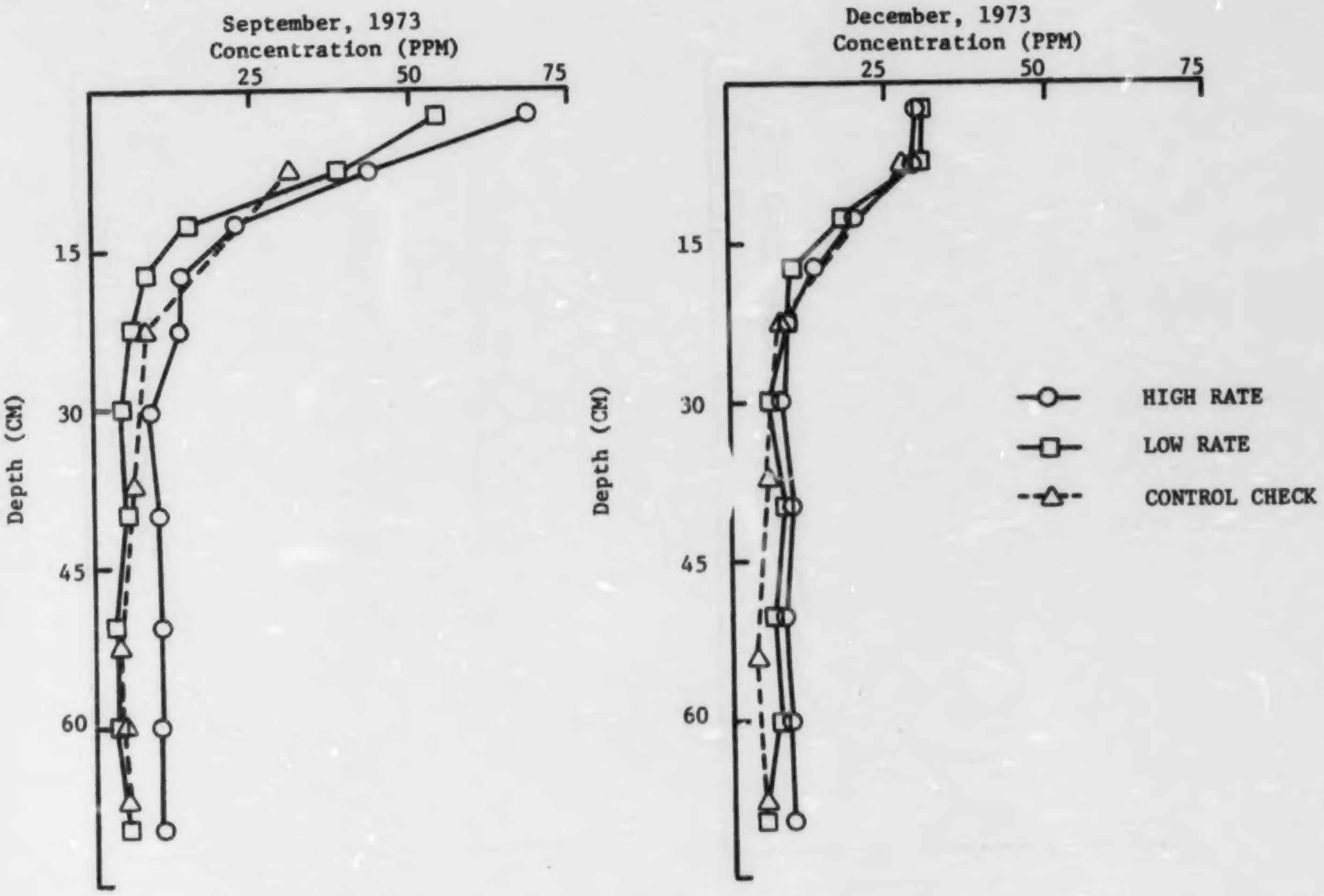


Figure 81. Soil profile magnesium concentrations for first-year application of swine lagoon effluent, 1973, at 1200 and 300 kg N/ha.

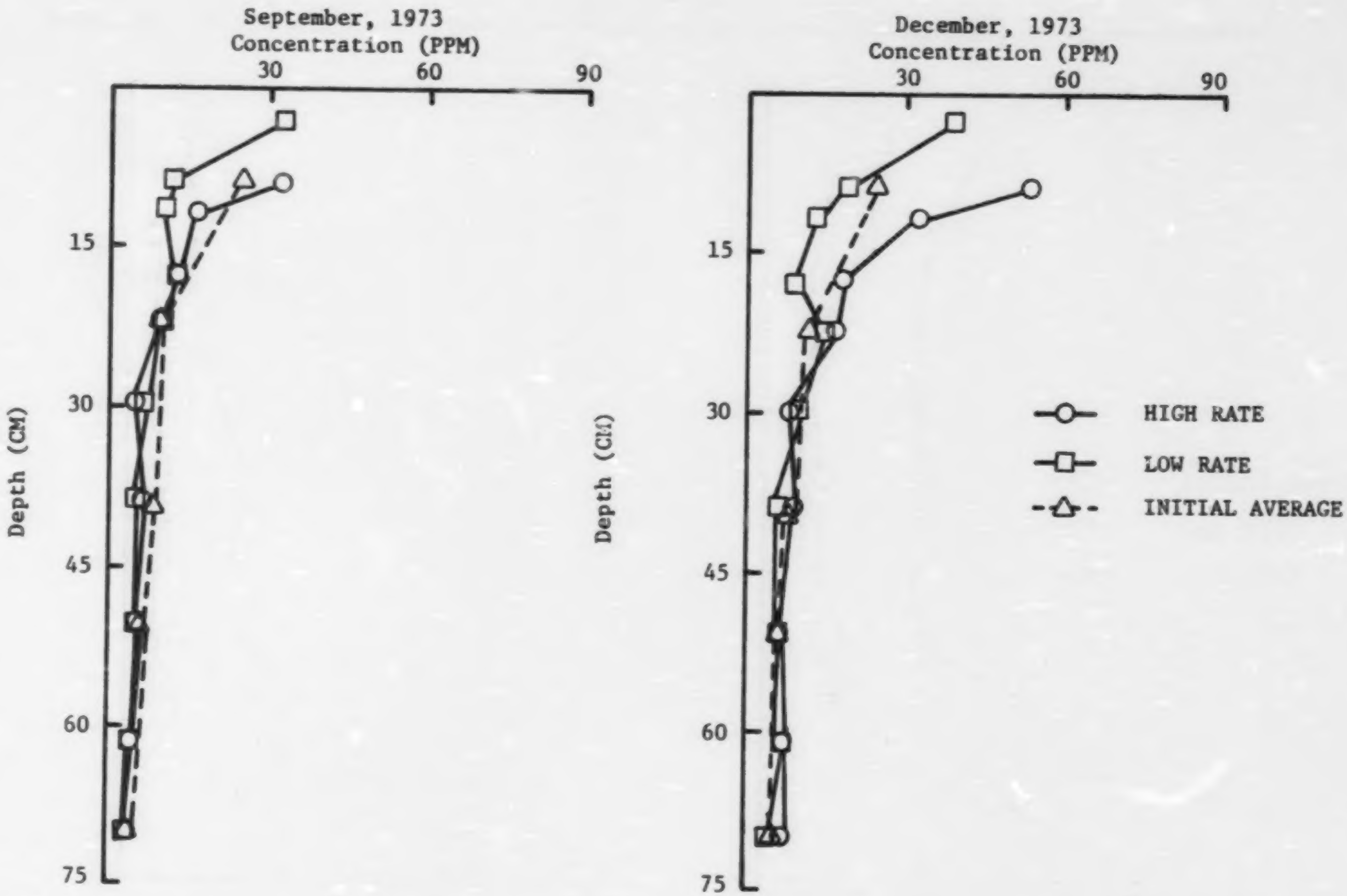


Figure 82. Soil profile phosphorous concentrations for first-year application of swine lagoon effluent, 1973, at 1200 and 300 kg N/ha.

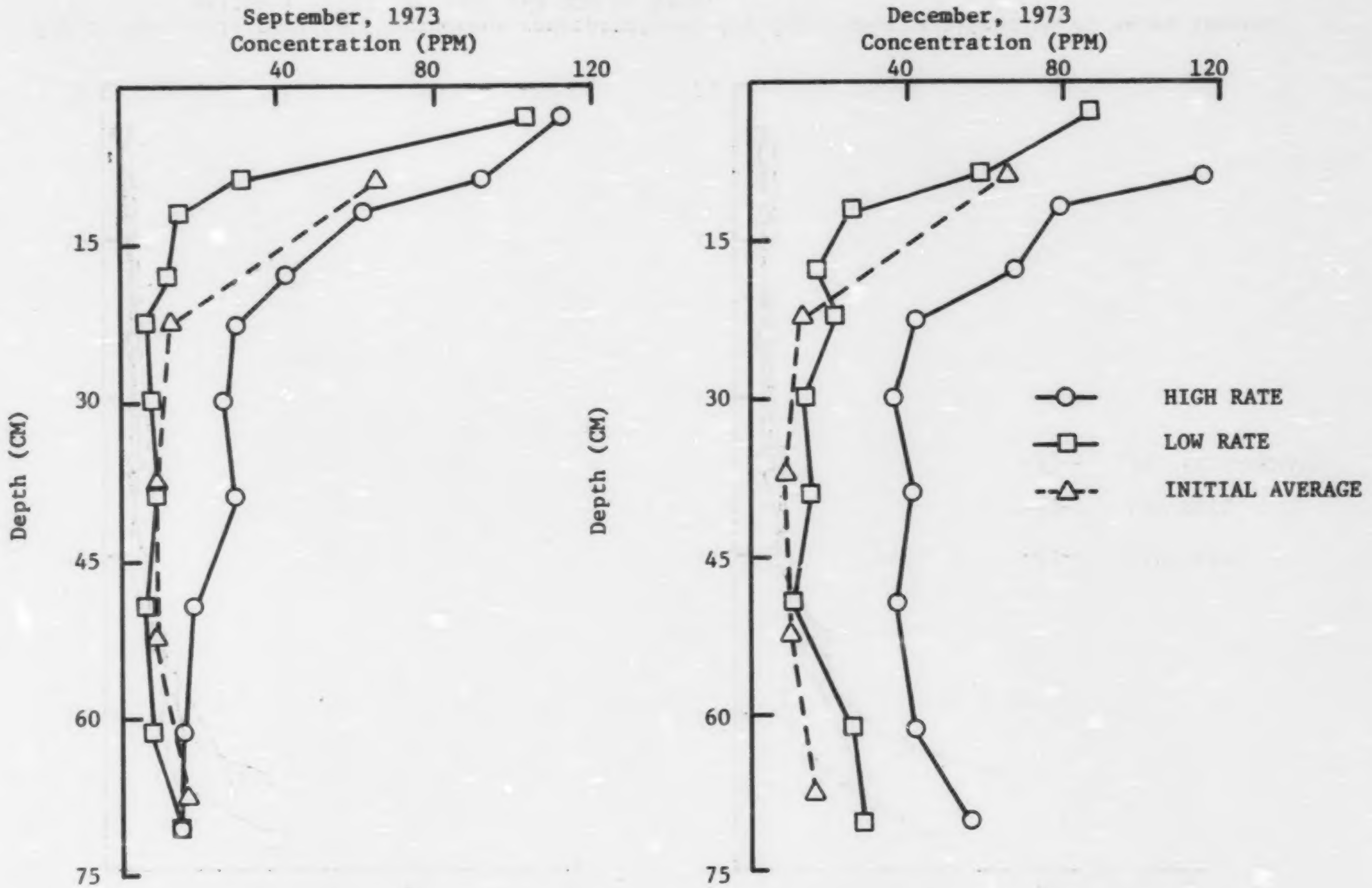


Figure 83. Soil profile potassium concentrations for first-year application of swine lagoon effluent, 1973, at 1200 and 300 kg N/ha.

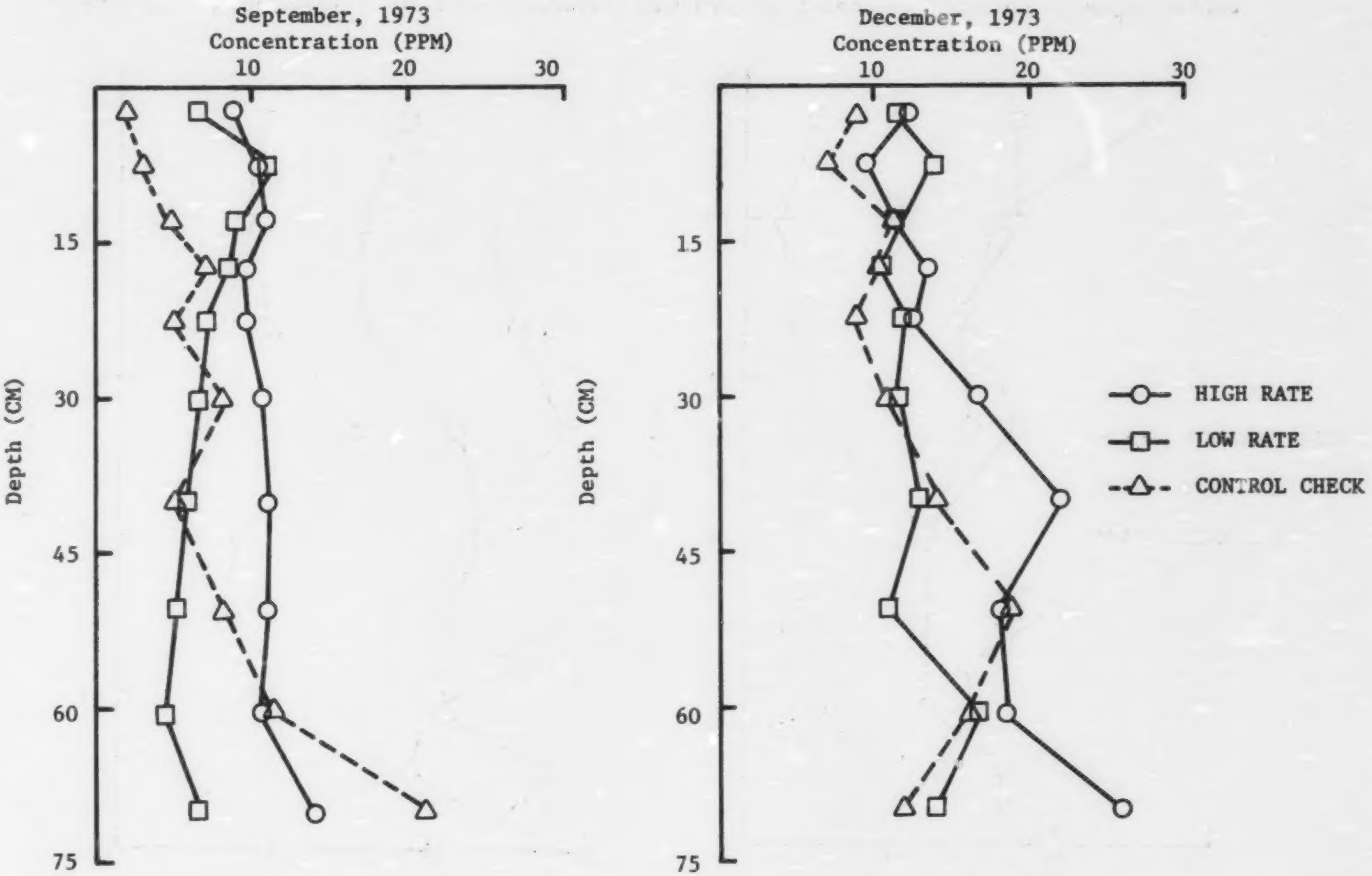


Figure 84. Soil profile sodium concentrations for first-year application of swine lagoon effluent, 1973, at 1200 and 300 kg N/ha.

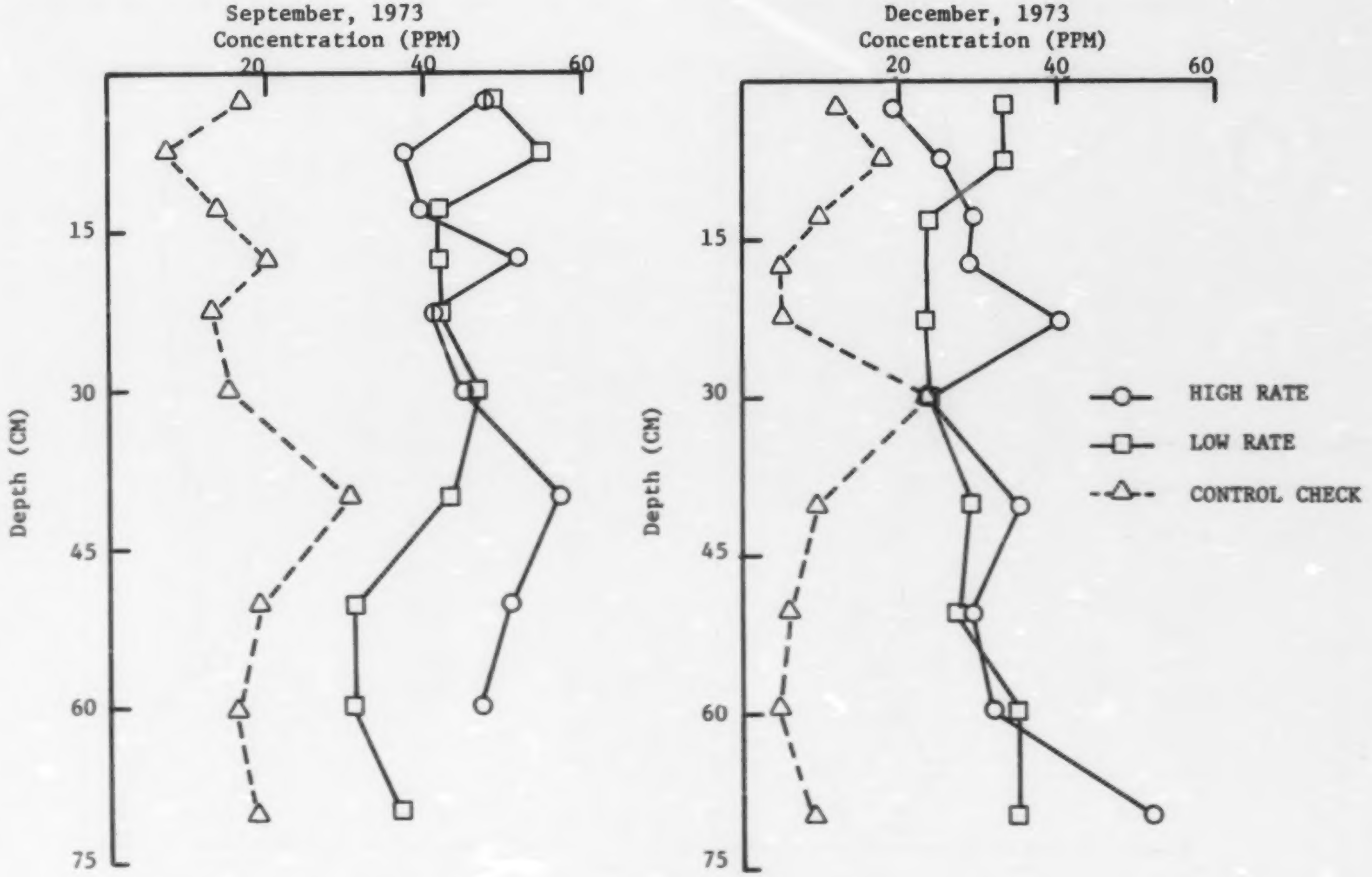


Figure 85. Soil profile chloride concentrations for first-year application of swine lagoon effluent, 1973, at 1200 and 300 kg N/ha.

had already occurred by September and both high and low rate plots were two- to three-fold higher in chloride concentration than control cores. During the following three winter months chloride leaching occurred with the December profiles nearly equal for the high and low application plots. However, December control core soil chloride levels remained lower than those in the effluent plots.

Trace elements Fe and Mn in the applied waste were also monitored along with the heavy metals Cu and Zn. For manganese, the high and low rate plots had nearly the same soil concentrations, Figure 86. These levels were greater than the control plots in the upper 50 cm of soil. There was little shift in soil Mn concentrations between September and December, 1973. Iron profiles in September were the same for all the waste applied and control plot cores, Figure 87. The same uniformity among cores was present in December but the absolute levels were about twice those found in September for reasons not apparent.

Copper levels reduced by 90 percent from the high growth stimulant levels in the swine feed on a ppm basis by lagoon pretreatment were only higher by 0.2 ppm in the upper 20 cm of soil in the heavy rate plots over the low rate plots, Figure 88. Zinc also evidenced a slightly higher surface zone accumulation for the high rate as compared to the low application rate, Figure 89, for both the September and December profiles. Control core data for copper and zinc were somewhat erratic. These trace elements were applied at quite low rates so that accumulation or leaching trends indicated after one year of data must be verified by further study.

The efficacy of detailed profile analysis in comparison to lumped analysis of the upper 75 cm of soil profile are demonstrated by comparing results in Tables 52 and 53 and Figures 78 - 89. Greater sensitivity in detecting initial trends was available with the soil concentrations profile.

Summarizing the soil accumulation results and conclusions for the total 75-cm profile, four waste constituents, NO_3-N, K, Na, and Cl were deduced to have increased significantly between low and high rate waste loadings above the control or initial soil levels on an overall mass balance. The other soil parameters, TKN, Ca, Mg, P, Cu, Zn, Fe and Mn were not significantly affected by loading rate although some were at higher levels than initial or control cores or had slightly elevated surface concentrations. Both Mg and Ca evidenced a surface accumulation but levels returned to control concentrations about three months after irrigation termination. This second group of constituents were either not applied at high rates compared to initial levels, were not reliably detected, or were leached from the upper 75 cm of soil and, hence, were not recorded as constituents that accumulated in the soil profile.

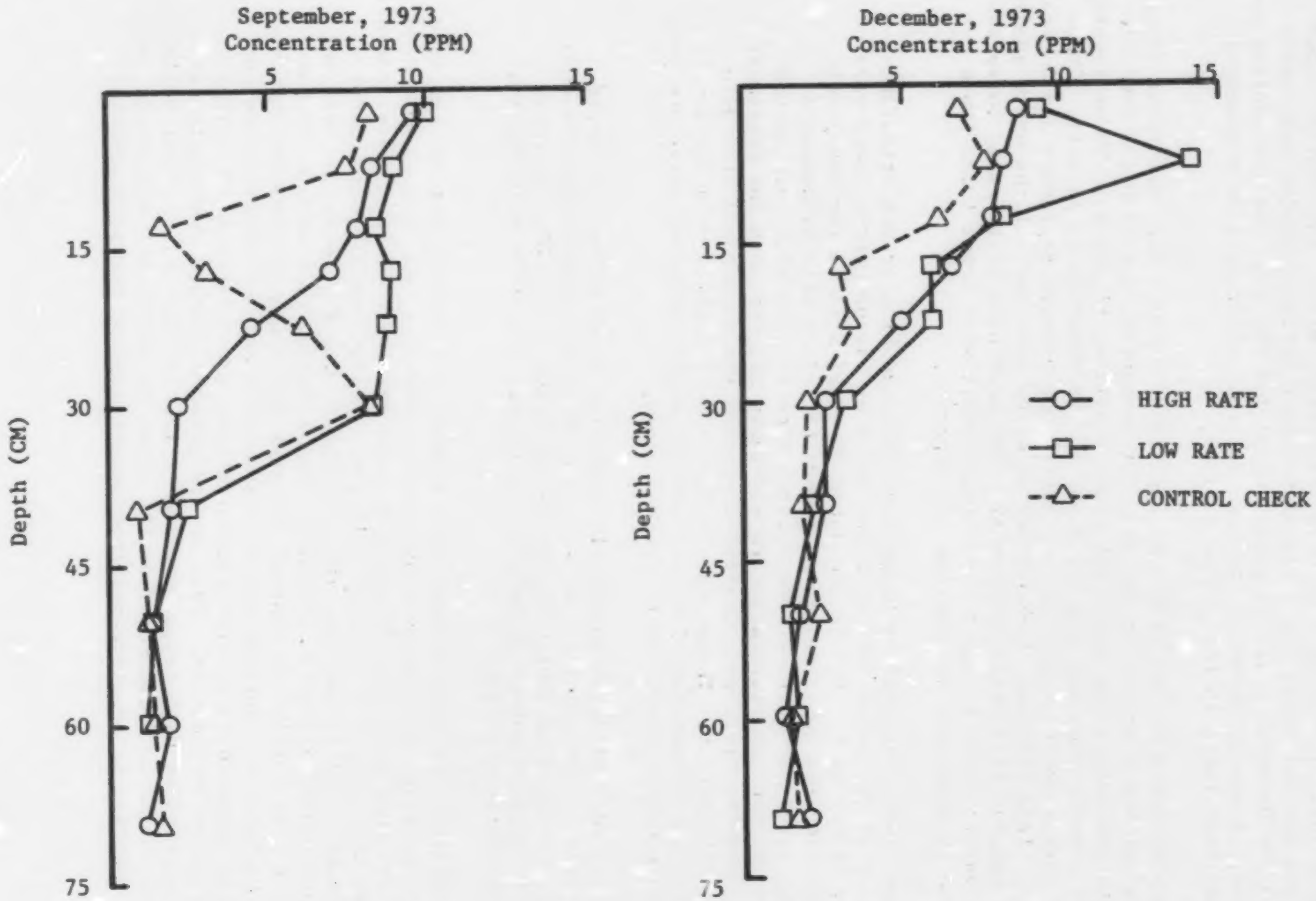


Figure 86. Soil profile manganese concentrations for first-year application of swine lagoon effluent, 1973, at 1200 and 300 kg N/ha.

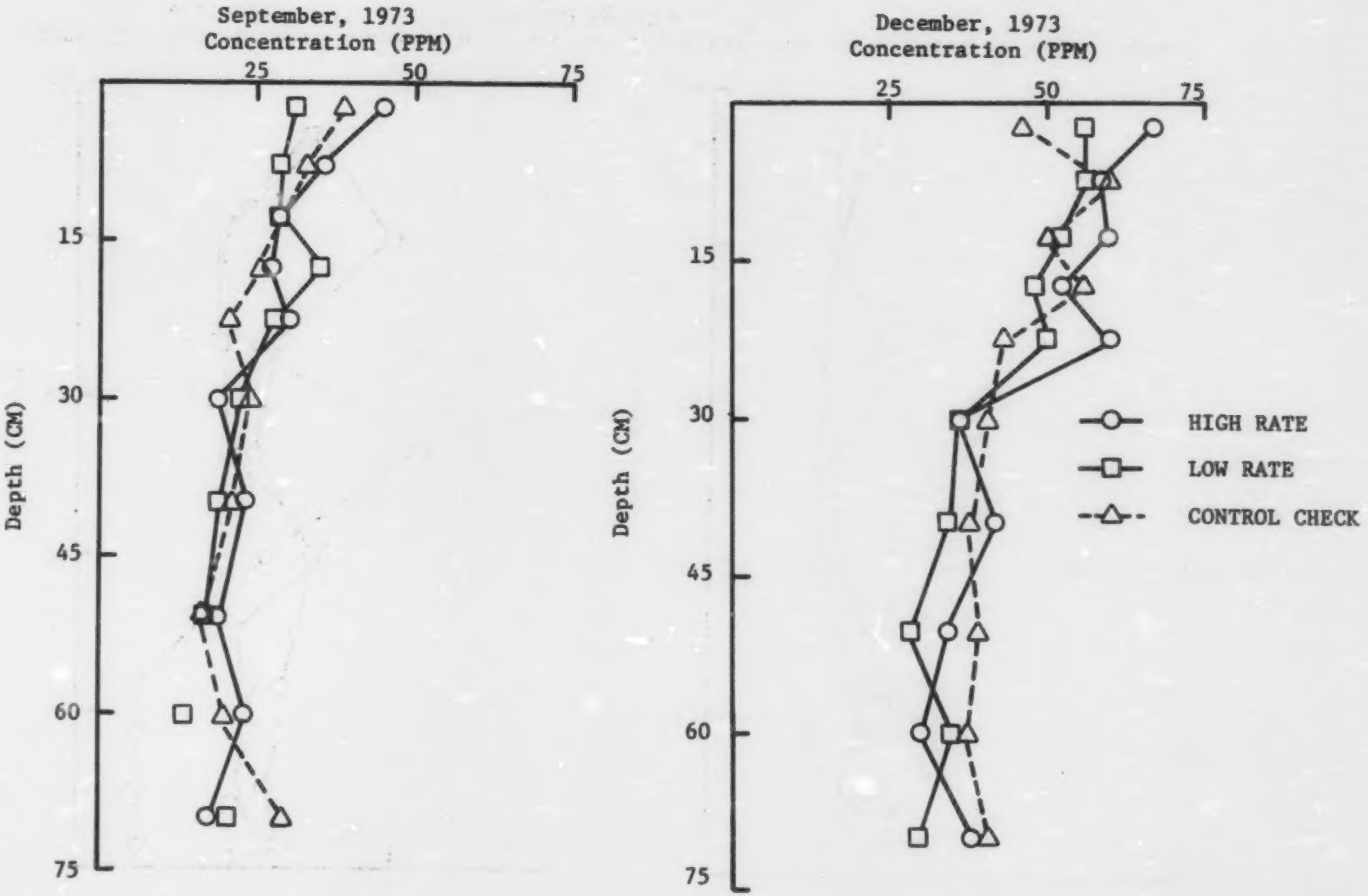


Figure 87. Soil profile iron concentrations for first-year application of swine lagoon effluent, 1973, at 1200 and 300 kg N/ha.

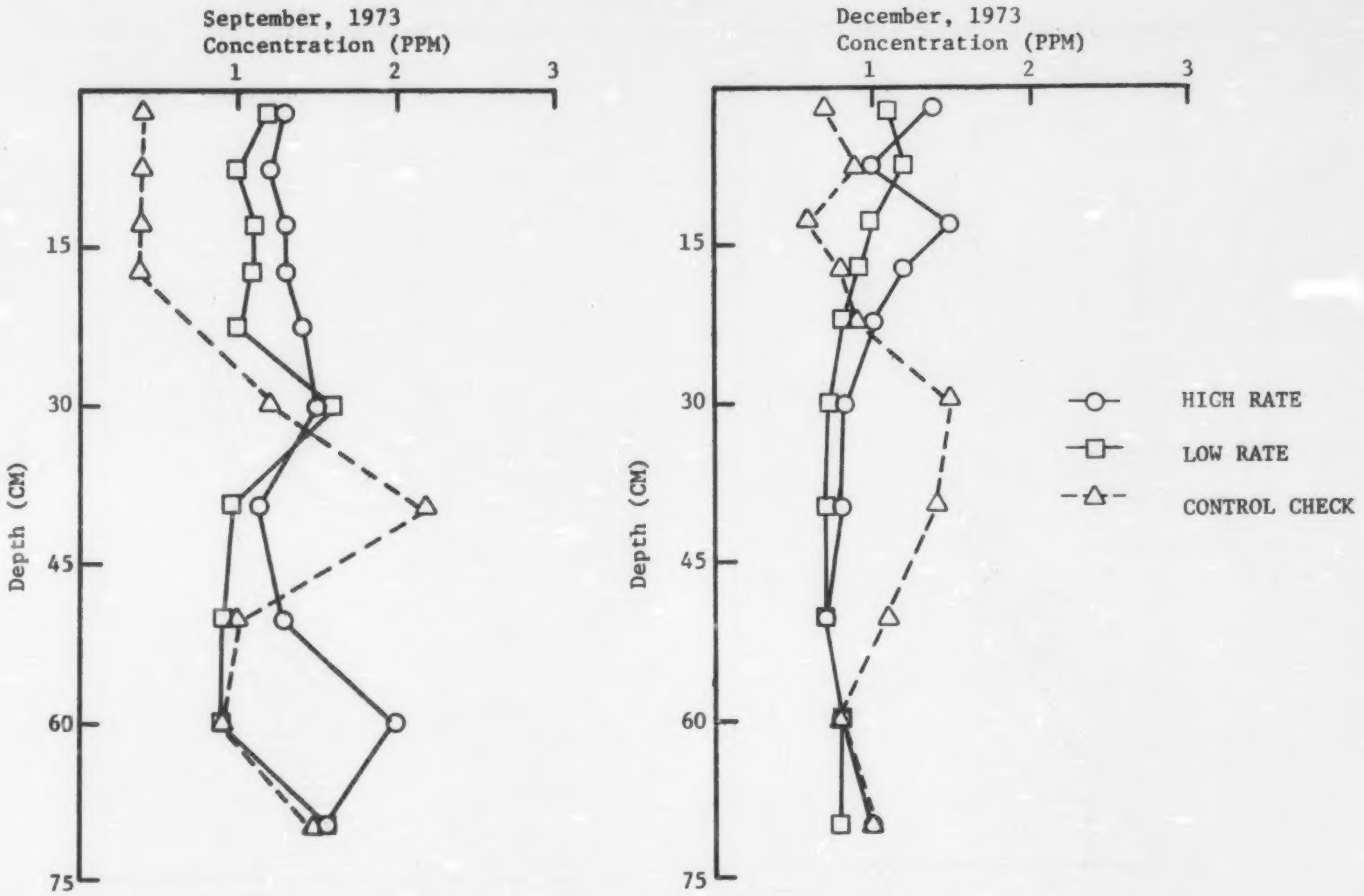


Figure 88. Soil profile copper concentrations for first-year application of swine lagoon effluent, 1973, at 1200 and 300 kg N/ha.

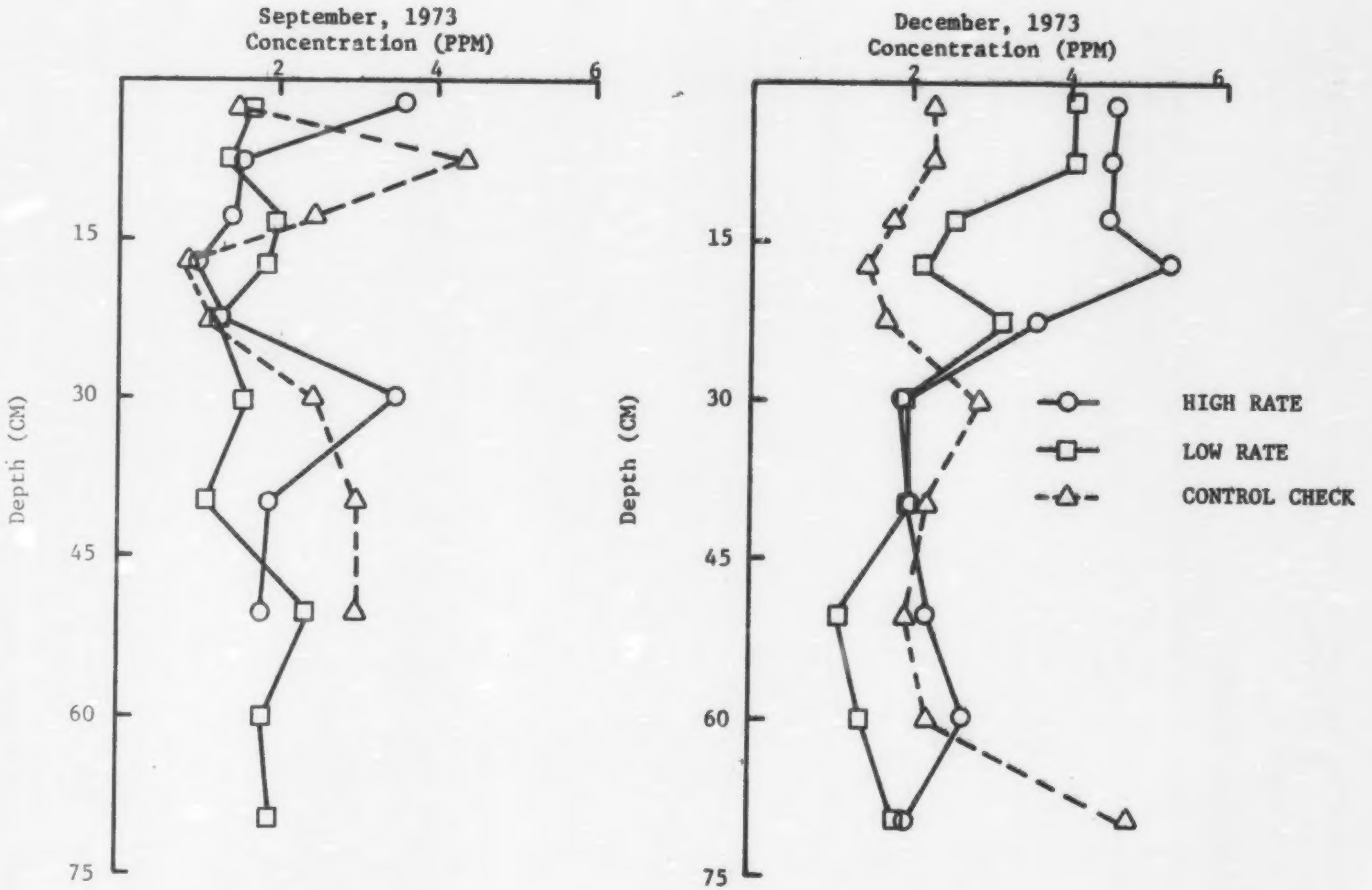


Figure 89. Soil profile zinc concentrations for first-year application of swine lagoon effluent, 1973, at 1200 and 300 kg N/ha.

Mass balance evaluations for control core Cu and Zn verified analytical difficulties and emphasized that these initial results should only be regarded as trends.

Field Plot Mass Balance

The mass balance on selected waste constituents consisted of comparison of inputs and those measured pathways or reservoirs for removal for the studied plant-soil system. The reference compartment or volume used in the mass balance was the upper 75 cm of soil volume beneath the triplicate plots receiving high, medium, and low levels of waste application. The common calculative basis was kilogram of parameter per hectare. Input consisted of the liquid which fell on the experimental plot area. The entire system balance from lagoon to plot to removal pathway was not used since a discussion of irrigation losses was covered earlier. The defined removal mechanisms were crop harvest, rainfall runoff, and soil accumulation. Differences between input and accounted for removals were labelled as unaccounted material.

The mass balance results were tabulated for each effluent loading rate, Tables 54 to 56. Rainfall runoff transport for 40 percent of the total rainfall runoff volume was found to represent approximately .5 percent to 2.5 percent of the total material applied with little difference between low and high application rates. Correcting these values by a ratio of total to analyzed runoff volume theoretically adjusted this loss mechanism to about 1 percent to 5 percent. During this initial study, runoff from surrounding plots not receiving effluent was not measured as a control or background assessment. Nonetheless, the absolute amounts of rainfall runoff transport were small. Additionally, the low and medium rates resulted in about the same rainfall runoff parameter amounts as measured with the high rate.

Crop removals as a percentage of applied material increased as the effluent application decreased. This was an expected trend since plant requirements are below applied levels and thus as the amount of applied nutrients decreased, the amount in the crop as percentage of that applied increased. The actual kg of the various waste materials measured in the harvested crop increased by nearly two-fold from the low to the medium rate and only slightly above the medium rate with the high application rate. These responses were similar to those described in the crop section for nitrogen reflecting the shape of the growth-response curves for these components.

Accumulation in the upper 75 cm of soil was treated as a removal or storage mechanism. Measurement accuracy depended on the ratio of applied to existing amounts of material and low rate additions of K, Na, and Cl were approximately equal to the initial amounts. Thus detection of soil accumulation was difficult for these components. At the high rate P and Mg, as well as K, Na, and Cl were applied at amounts greater than the initial soil contents, hence the reliability of these soil analyses was increased in the high rate plots.

Table 54. OVERALL MASS BALANCE FOR FIRST-YEAR APPLICATION OF SWINE LAGOON EFFLUENT AT THE HIGH RATE TO A COASTAL BERMUDA GRASS - NORFOLK SOIL PLOT SYSTEM (AVERAGE OF THREE REPLICATES)

Parameter	Input, output, and accumulation, kg/ha					
	Initial amount	Applied effluent	Crop uptake	Rainfall runoff[a]	Accumulation, September, 1973	Unaccounted for
TKN	2,890	1,180	428	2.2	176	[illegible]
P	145	268	36	2.6	28	579
Ca	814	282	72	2.2	-46	204
Mg	149	332	42	0.9	73	254
K	262		413	6.2	174	216
Na	119	470	26	2.1	11	612
Cl	176	762	116	7.8	427	431
Cu	10.9	2.7	0.25	0.034	6.8	212
Zn	40	3.0	0.43	--	--	-4.5
Mn	36	2.1	1.18	--	--	--
Fe	411	8.1	4.1	--	--	

[a] Evaluated for events totalling about 40 percent of total runoff

Table 55. OVERALL MASS BALANCE FOR FIRST YEAR-APPLICATION OF SWINE LAGOON EFFLUENT AT MEDIUM RATE TO A COASTAL BERMUDA GRASS - NORFOLK SOIL PLOT SYSTEM (AVERAGE OF THREE REPLICATES)

Parameter	Input, output, and accumulation, kg/ha					
	Initial amount	Applied effluent	Crop uptake	Rainfall runoff[a]	Accumulation, September, 1973	Unaccounted for
TKN	2,264	592	336	1.3	11.2	243
P	142	134	31	0.8	2.2	104
Ca	820	141	53	1.3	-24	110
Mg	118	166	32	0.4	62	71
K	262	603	339	2.5	44	217
Na	119	235	24	1.3	19	190
Cl	176	382	128	4.5	334	-84
Cu	11	1.3	0.21	0.01	15	-13.9
Zn	40	1.5	0.36	--	--	--
Mn	36	1.0	0.83	--	--	--
Fe	411	4.0	3.7	--	--	--

Table 56. OVERALL MASS BALANCE FOR FIRST-YEAR APPLICATION OF SWINE LAGOON EFFLUENT AT THE LOW RATE TO A COASTAL BERMUDA GRASS - NORFOLK SOIL PLOT SYSTEM (AVERAGE OF THREE REPLICATES)

	Input, output, and accumulation, kg/ha					
Parameter	Initial amount	Applied effluent	Crop uptake	Rainfall runoff[a]	Accumulation, September, 1973	Unaccounted for
TKN	2,386	297	207	2.1	-11	96
P	144	67	20	1.3	-37	83
Ca	710	71	33	1.1	-58	94
Mg	129	83	18	0.46	11	53
K	315	301	207	4.5	-96	184
Na	119	118	11	1.4	-37	141
Cl	176	190	87	3.4	316	-216
Cu	11	0.67	0.12	0.028	3.5	-2.9
Zn	40	0.78	0.27			
Mn	36	0.56	0.50			
Fe	411	2.0	1.9			

The difference between input and accounted for amounts of the various parameters was termed unaccounted material, Tables 54, 55, and 56. The unaccounted material was attributed to leaching losses from the studied upper 75 cm of soil. However, in the case of phosphorus, which is not highly mobile in these soils, the unaccounted material certainly contained losses to soil states not evaluated by the analytical tests used. The leaching losses of other ions could not be separated between vertical losses through the B horizon and more horizontal or downslope losses with water flow along the interface of the A and B horizons.

Unaccounted material was about the same for the low and medium rate plots except for nitrogen which increased from 100 kg/ha. to 250 kg/ha. The high rate plots had nearly a two-fold increase in unaccounted materials, including nitrogen, over the medium rate plots. Attributing these losses conclusively to leaching after this first year study was not possible because the anticipated relative freedom of movement or mobility of these constituents was not verified. That is, K, Na, and Cl should have been much more mobile in the soil than the Ca, Mg, or P. However, the leaching losses as a percentage of the amount applied or applied plus initially present were not significantly greater for K, Na, and Cl as compared to P, Ca, and Mg, Table 57. Thus other factors, yet unsubstantiated, prevented in depth conclusions regarding mass balances or pathways for removal of waste constituents. Extension of these studies over several years would allow greater application levels so that accumulation could be more easily documented. Also, several years of data would reduce annual variability of crop uptake and rainfall runoff as related to the total system mass balance.

Table 57. PERCENTAGES OF VARIOUS WASTE CONSTITUENTS REMOVED BY THE MAJOR PLANT-SOIL SYSTEM PATHWAYS FOR THE COASTAL BERMUDA-COASTAL PLAINS EXPERIMENT RECEIVING ONE SEASON OF SWINE LAGOON EFFLUENT

Parameter	Crop removal, percent of input			Rainfall, runoff, percent of input[a]			Unaccounted for, percent of input			Unaccounted for, percent of input plus initial		
	High	Medium	Low	High	Medium	Low	High	Medium	Low	High	Medium	Low
TKN	36	57	70	0.5	0.6	1.8	49	41	33	14	8	4
P	13	23	30	2.5	1.5	3.5	75	78	123	48	38	39
Ca	25	37	46	2	2.5	4	90	79	134	23	12	12
Mg	12	20	22	0.75	0.5	1.4	65	43	65	45	25	25
K	34	56	69	1.2	1.0	3.8	51	36	62	42	25	30
Na	5	10	10	1.0	1.2	2.8	92	81	121	73	54	60
Cl	15	33	46	2.5	3.0	4.5	28	-22	-113	22	-15	-59
Cu	9	16	18	3.0	2.0	10	-167	-1,000	-433	-33	-111	-25

[a] Scaled up from values measured for 40 percent of runoff by means of a proportional ratio

SECTION VIII

REFERENCES

1. Jones, J. R. Estimated Swine Situation Reports by County Extension Workers. N. C. State University, Raleigh, N. C. 1972.

2. N. C. Department of Agriculture, USDA Federal-State Crop Reporting Service. December 31, 1974.

3. Robbins, J. W. D., D. H. Howells, and G. J. Kriz. Role of Animal Wastes in Agricultural Land Runoff. Water Pollution Control Research Series. EPA Report 13020 DGX. August 1971. 114 p.

4. Muehling, A. J. Swine Housing and Waste Management. A Research Review, AEnd-873. Department of Agricultural Engineering, University of Illinois, Urbana - Champaign. August 1969. 91 p.

5. Taiganides, E. P. Characteristics and Treatment of Wastes From a Confinement Hog Production Unit. Unpublished Ph.D. Thesis, Department of Agricultural Engineering, Iowa State University, University Microfilm, Ann Arbor, Michigan. 1963.

6. Arial, J. D. The Influence of Feed Additives on the Biochemical Oxygen Demand Analysis for Swine Wastes. M.S. Thesis, N. C. State University, Raleigh, N. C. 1970.

7. Humenik, F. J., M. R. Overcash, and L. B. Driggers. Swine Production Industry - Waste Characterization and Management. Department of Biological and Agricultural Engineering, N. C. State University, Raleigh, N. C. 1973. 56 p.

8. Scholze, H. G. Systems for the Dehydration of Livestock Wastes, A Technical and Economical Review. Proc. Int'l. Symp. on Livestock Wastes. ASAE PROC-271:27-29. 1971.

9. Van Arsdall, R. N. The Economic Value of Manure from Confinement Finishing of Hogs. University of Illinois Agricultural Experiment Station Bulletin 687, Urbana, Illinois. May 1962.

10. McKinney, Ross E. Manure Transformations and Fate of Decomposition Products in Water. Proceedings of the Conference Concerning the Role of Agriculture in Clean Water, Iowa State University, Ames, Iowa. 1970.

11. Dale, A. C. Aerobic Treatment of Animal Wastes. ASAE Paper No. 67-927A. 1967.

12. Hart, S. A. and M. E. Turner. Lagoons for Livestock Manure. J. Water Pol. Cont. Fed. 37:1578-1596, November 1965.

13. Eby, H. J. Design Criteria for Manure Lagoons. Paper presented at the Annual Meeting of American Society of Animal Meat Producers, Chicago, Illinois. 1961.

14. Eby, H. J. Manure Disposal Lagoons. USDA, ARS 42-75. 1963.

15. Eby, H. J. Correcting Malfunctioning Lagoons. USDA, Agricultural Research Service, Agricultural Engineering Research Division. Mimeo. 1964. 8 p.

16. Clark, C. E. How Are Lagoons Working on Hog Farms? ASAE Paper No. 64-419. 1964.

17. Clark, C. E. Hog Waste Disposal by Lagooning. J. San. Eng. Div., ASCE. 91:27-41, June 1965.

18. Dale, A. C. Oxidation Lagoons. In: Farm Animal Wastes, 1969. Regional Bulletin NC-69. 1969.

19. Dornbush, J. N. State of the Art - Anaerobic Lagoons. 2nd International Symposium for Waste Treatment Lagoons, Kansas City, Missouri. 1970. pp. 382-387.

20. Oswald, W. J. Advances in Anaerobic Pond Systems Design. Advances in Water Quality Improvement, University of Texas Press, Austin, Texas. 1968. p. 409.

21. Loehr, R. C. Pollution Implications of Animal Wastes - A Forward - Oriented Review. U. S. Dept. Int., Fed. Water Pol. Control Adm., R. S. Kerr Water Res. Center. Ada, Oklahoma. 1968.

22. Loehr, R. C. Anaerobic Lagoons: Considerations in Design and Application. Transactions ASAE. 11:320-330. March 1968.

23. Taiganides, E. P. Theory and Practice of Anaerobic Digesters and Lagoons. 2nd National Poultry and Litter Waste Management Seminar Proceedings, College Station, Texas, 1968. p. 200-221.

24. Ricketts, R. L. Lagoons for Disposal of Wastes from Hog Feeding Floors. ASAE Paper No. 60-402. 1960.

25. Jedele, D. G. and E. L. Hansen. Handling Hog Manure As a Liquid. University of Illinois College of Agriculture Circular 820. 1960.

26. Eby, H. J. Anaerobic Lagoons - Theory and Practice. 2nd National Symposium on Poultry Industrial Waste Management Proceedings, Lincoln, Nebraska. 1964. p. 77-91.

27. Soil Conservation Service. Interim Specifications - Disposal Lagoons, Advisory ENG-5, USDA, Washington, D.C. 1970.

28. Soil Conservation Service. National Engineering Standard, Disposal Lagoons. 1971.

29. Willrich, T. L. Primary Treatment of Swine Wastes by Lagooning. Proc. Nat'l. Symp. on Animal Waste Management. ASAE Pub. SP-0366:70-74. 1966.

30. Dornbush, J. N. and J. R. Anderson. Lagooning of Livestock in South Dakota. Proc. 19th Ind. Waste Conference, Purdue University. 1964. p. 317-325.

31. Curtis, D. R. Design Criteria for Anaerobic Lagoons for Swine Manure Disposal. Proc. Nat'l. Symp. on Animal Waste Management. ASAE Pub SP-0366:75-80. 1966.

32. Midwest Plan Service. AED-1. Ames, Iowa. August 1969. 2 p.

33. Lynn, H. P. The Effects of Loading Rates on the Design and Operation of Anaerobic Swine Lagoons. Summary of Unpublished M.S. Thesis, Clemson University, Clemson, South Carolina. 1968.

34. Miner, J. R. Anaerobic Treatment of Animal Wastes. In: Farm Animal Wastes, 1969. Regional Bulletin NC-69. 1969.

35. Barr, H. T., B. A. Tower, C. D. Steelman, and L. J. Cabes, Jr. Farm Lagoons in Louisiana. Louisiana State University Agricultural Experiment Station Bulletin No. 638. 1969.

36. Baldwin, L. B. and R. A. Nordstedt. Design Procedures for Animal Waste Treatment Lagoons in Florida. Paper No. SE 71-214 presented at the Southeast Regional Meeting of ASAE, Jacksonville, Florida. 1971.

37. Hermanson, R. E. and H. Watson. Manure Disposal Lagoons. Agricultural Experiment Station Circular R-6, Auburn University, Auburn, Alabama. 1968.

38. State of Tennessee. Engineering Standard, Animal Waste Disposal System. Department of Public Health, Nashville, Tennessee 1973.

39. American Society of Agricultural Engineers. Tentative Guidelines For Lagoons. Development being coordinated for SE-412 Committee by C. L. Barth, Clemson University, Clemson, South Carolina.

40. Nordstedt, R. A. and C. L. Barth. Animal Waste Lagoons--Research and Design in the Southeast. Paper presented at the Southeast Regional Meeting of ASAE, Memphis, Tennessee. 1974.

41. Nordstedt, R. A., L. B. Baldwin, and C. C. Hortenstine. Multistage Lagoon Systems for Treatment of Dairy Farm Waste--Progress Report. Presented at the Southeast Regional Meeting of ASAE, Jacksonville, Florida. Paper No. SE 71-403. 1971.

42. Barsom, George, Lagoon Performance and the State of Lagoon Technology. Environmental Protection Technology Series EPA-R2-73-144. 1973.

43. Missouri Basin Engineering Health Council. Waste Treatment Lagoons - State-of-the-Art. Water Pollution Control Research Series, Project 17090 EHS, EPA, Washington, D. C. July 1971.

44. WPCF Manual of Practice No. 11. Operation of Wastewater Treatment Plants. Water Pollution Control Federation, Washington, D.C. 1970.

45. McGhee, T. J. Volatile Acid Concentration in Batch Fed Anaerobic Digesters. Water and Sewage Works. 118:130. May 1971.

46. Dale, A. C. Status of Dairy Cattle Waste Treatment and Management Research. Proceedings National Symposium on Animal Waste Management, Warrenton, Virginia. 1971. p. 85-95.

47. Loehr, R. C. Alternatives for Treatment and Disposal of Animal Wastes. J Water Pol. Cont. Fed. 43:668-678. 1971.

48. Jones, D. D., D. O. Day, and A. C. Dale. Aerobic Treatment of Livestock Wastes. Experiment Station Bulletin 737, University of Illinois, Urbana - Champaign, Illinois. 1970.

49. Irgens, R. L. and D. L. Day. Aerobic Treatment of Swine Wastes. Proc. Nat'l. Symposium on Animal Waste Management. ASAE Pub. SP-0366:58-30. 1966.

50. McKinney, R. E. and R. Bella. Water Quality Changes in Confined Hog Waste Treatment. Kansas Water Resources Res. Inst. Report No. 24, University of Kansas, Lawrence. December 1967.

51. McCalf and Eddy, Inc. Wastewater Engineering. McGraw-Hill, New York. 1972.

52. Grune, N. N., R. E. Cossitt, and R. H. Philp. An Aerobic Process Automation by Orp Conductivity and Gas Chromatography. Purdue University Engineering Extension Service No. 92-95. 1957. p. 604-635.

53. Ludington, D. C. Oxidation-Reduction Potential, Control by Aeration and Influence on Odor Production and Degradation of Chicken Manure. Unpublished Ph.D Dissertation, Purdue University Lafayette, Indiana. 1968.

54. Converse, J. C. K. L. Day, J. T. Pfeffer, and B. A. Jones, Jr. Aeration with ORP Control to Supress Odors Emitted from Liquid Swine Manure Systems. Proc. Int'l. Symposium on Livestock Wastes. ASAE PROC-271:267-271. 1971.

55. Adriano, D. C., P. F. Pratt, and S. E. Bishop. Fate of Organic Forms of N and Salt from Land-Disposed Manures from Dairies. Livestock Waste Management and Pollution Abatement, Proc. Int. Symposium on Livestock Wastes, ASAE, St. Joseph, Michigan. 1971. p. 243-246.

56. Mathers, A. C., B. A. Stewart, J. D. Thomas, and B. J. Blair. Effects of Cattle Feedlot Manure on Crop Yields and Soil Conditions. USDA Southwestern Great Plains Research Center, Technical Report #11, Symposium on Animal Waste Management, Bushland, Texas. 1973.

57. Pratt, P. F., F. E. Broadbent, and J. P. Martin. Using Organic Wastes as Nitrogen Fertilizers. California Agriculture. June 1973.

58. Koelliker, J. K. and J. R. Miner. Use of Soil to Treat Anaerobic Lagoon Effluent Renovation as a Function of Depth and Application Rate. Transactions of the ASAE. 13:496-499. 1970.

59. Olsen, R. J., R. F. Hensler, and O. J. Attoe. Effect of Manure Application, Aeration, and Soil pH on Soil Nitrogen Transformations and on Certain Soil Test Values. Soil Science Society Amer. Proc. 34:222-225. 1970.

60. Wallingford, G. W. Effects of Solid and Liquid Beef Feedlot Wastes on Soil Characteristics and on Growth and Composition of Corn Forage. Ph.D. Thesis, Kansas State University, Manhattan, Kansas. 1974.

61. Meek, B. D., A. J. MacKenzie, T. J. Donovan, and W. F. Spencer. The Effect of Large Applications of Manure on Movement of Nitrate and Carbon in an Irrigated Desert Soil. J Envron. Quality. 3:253-258, 1974.

62. Hedges, J. D., E. T. Kornegy, and D. C. Marteno. Effect of Applying Swine Feces on Soil and Plant Mineral Levels. Virginia Polytechnic Institute and State University, Blacksburg. J. Animal Sci. 37:281. 1973.

63. Chaney, R. L. Crop and Food Chain Effects of Toxic Elements in Sludges and Effluents. Proc. Conf. on Recycling Municipal Sludges and Effluents on Land. EPA, Champaign, Illinois. 1973.

64. Humenik, F. J. Swine Waste Characterization and Evaluation of Animal Waste Treatment Alternatives. Water Resources Research Institute of University of North Carolina, Report No. 61., Raleigh, N. C. 1972.

65. Miner, J. R. and T. L. Willrich. Livestock Operations and Field-Spray Manure as Sources of Pollutants. In: Agricultural Practices and Water Quality, Iowa State University, Ames, Iowa. 1970. p. 231-240.

66. Robbins, J. W. D., D. H. Howells, and G. J. Kriz. Stream Pollution from Animal Production Units. J. Water Pol. Cont. Fed. 44:1536-1544, August 1972.

67. McCaskey, T. A., G. H. Rollins, and J. A. Little. Water Pollution by Dairy Farm Wastes as Related to Method of Waste Disposal. WRRI Bul. 18, Auburn University, Auburn, Alabama. 1973.

68. Miner, J. R., L. R. Fina, J. W. Funk, R. I. Lipper, and G. H. Larson. Stormwater Runoff from Cattle Feedlots. Proc. Nat'l. Symposium on Animal Waste Management. ASAE Pub. No. SP-0366: 23-27. 1966.

69. Gilbertson, C. B., T. M. McCalla, J. R. Ellis, O. E. Cross, and W. R. Woods. The Effect of Animal Density and Surface Slope on Characteristics of Runoff Solid Wastes and Nitrate Movement on Unpaved Beef Feedlots. University of Nebraska Agr. Exp. Sta. Pub. SB508. 1970. p. 23.

70. Madden, J. M. and J. N. Dornbush. Measurement of Runoff and Runoff Carried Waste from Commercial Feedlots. Proc. Int'l. Symposium on Livestock Wastes. ASAE PROC.-271:44-47. 1971.

71. McCalla, T. M., J. R. Ellis, C. B. Gilbertson, and J. R. Woods. Chemical Studies of Solids, Runoff, Soil Profile and Groundwater from Beef Cattle Feedlots at Mead, Nebraska. Proc. Cornell Agr. Waste Management Conference. 1972. p. 211-233.

72. APHA. Standard Methods for the Examination of Water and Waste-Water. 12 ed. American Public Health Association, Inc., New York. 1965.

73. Overcash, M. R., D. L. Reddell, and D. L. Day. Chemical Analysis. ASAE Paper No. 74-4546. 1974.

74. Humenik, F. J. and M. R. Overcash. Discussion of Paper, Evaluation of Methods for the Analysis of Physical, Chemical and Biochemical Properties of Poultry Wastewater, by Prakasam, *et al*. ASAE Workshop, Chicago, Ill. December 1972.

75. Busch, A. W. Aerobic Biological Treatment of Waste Waters. Houston, Oligodynamics Press, 1971. 416 p.

76. Taylor, E. W., N. P. Burman, and C. V. Oliver. Membrane Filtration Technique Applied to the Routine Bacteriological Examination of Water. Journal of the Institute of Water Engineers. 9:248-254. January 1955.

77. Kabler, P. W. and H. F. Clark. Coliform Group and Fecal Coliform Organisms as Indicators of Pollution in Drinking Water. Journal American Water Works Association. 52:1577-1579. February 1960.

78. Geldreich, E. E., H. F. Clark, C. B. Huff, and L. C. Best. Fecal Coliform Organism Medium for the Membrane Filter Technique. Journal American Water Works Association. 57:208-214. February 1965.

79. Overcash, M. R., F. J. Humenik, and L. B. Driggers. Swine Production and Waste Management: State of the Art. Proc. Third International Symposium on Livestock Waste Management, In Press. Urbana-Champaign, Illinois. April 1975.

80. Jett, S. C., H. E. Hamilton, and I. J. Ross. Settling Characteristics of Swine Manure. ASAE Trans., In Press.

81. Smith, R. J., C. V. Booram, and T. E. Hazen. Some Chemical and Physical Aspects of Phosphate Precipitation from Anaerobic Liquors Derived from Animal Waste Treatment Lagoons. ASAE Paper No. 73-4522. (Presented at ASAE Meeting. Chicago, Illinois. 1973).

82. Miner, J. R. and J. I. Koelliker. Resorption of Ammonia From Anaerobic Lagoons. Iowa Agric. and Home Economics Experiment Station, Journal Paper No. J-6873. 1973.

83. EPA. Development Document for Proposed Effluent Limitations Guidelines and New Source Performance Standards for the Feedlots Point Source Category. Office of Air and Water Programs, Washington, D.C. August 1973. 302 p.

84. Moore, J. A., M. R. Overcash, and T. B. S. Prakasam. Animal Waste Sample Preservation and Preparation. ASAE Paper No. 74-4545. (Presented at ASAE Meeting. Chicago, Illinois. 1974).

85. Lutz, J. F. Movement and Storage of Water in North Carolina Soils. N. C. Agricultural Experiment Station Sorts Information Series No. 15. April 1970.

86. Overcash, M. R., J. W. Gilliam, and F. J. Humenik. Lagoon Pretreatment: Selected Heavy Metals and Cation Removals, In Press.

87. Larsen, V., J. H. Axley, and G. L. Miller. Agricultural Wastewater Accommodation and Utilization of Various Forages. Univ. of Ind. Water Resources Research Center. Technical Report No. 19. 1972.

88. Doss, B. D., D. A. Ashley, O. L. Bennett, and R. M. Patterson. Interactions of Soil Moisture, Nitrogen, and Clipping Frequency on Yield and Nitrogen Content of Coastal Bermuda Grass. Agron. J. 58:510-512. 1966.

89. Woodhouse, W. W., Jr. Long-Term Fertility Requirements of Coastal Bermuda II Nitrogen, Phosphorus, and Lime. Agron. J. 61:251-256. 1969.

90. Woodhouse, W. W., Jr. Long-Term Fertility Requirements of Coastal Bermuda I. Potassium. Agron. J. 60:508-512. 1968.

91. Burton, G. W., W. S. Wilkinson, and R. L. Carter. Effect of Nitrogen, Phosphorus, and Potassium Levels and Clipping Frequency on Forage Yield and Protein, Carotene, and Xanthophyll Content of Coastal Bermuda Grass. Agron. J. 61:60-63. 1969.

92. Murrmann, R. P. and F. R. Koutz. Role of Soil Chemical Processes in Reclamation of Wastewater Applied to Land. In: Wastewater Management by Disposal on Land, Corps of Eng. Cold Region Research and Eng. Lab., Hanover, N. H. 1972.

93. Hunt, P. Microbial Responses to the Land Disposal of Secondary-Treated Municipal-Industrial Wastewater. In: Wastewater Management by Disposal on Land, Corps of Eng. Cold Region Research and Eng. Lab., Hanover, N. H. 1972.

94. Burd, J. S. and J. C. Martin. Secular and Seasonal Changes in the Soil Solution. Soil Science 18, 151-167, 1924.

SECTION IX

PUBLICATIONS ASSOCIATED WITH PROJECT RESULTS

Humenik, F. J., R. W. Skaggs, C. R. Willey, and D. Huisingh. Evaluation of swine waste treatment alternatives. Proceedings Cornell University Conference on Agricultural Waste Management. pp 341-352. 1972.

Humenik, F. J. and M. R. Overcash. Analyzing Physical and Chemical Properties of Liquid Wastes. ASAE Proceedings SP-0275, Standardizing Properties and Analytical Methods Related to Animal Waste Research. pp 114-182. St. Joseph, Michigan, 1975.

Humenik, F. J. The latest in swine waste disposal. Proceedings North Carolina Pork Producers Conference. pp 43-46. January 1973.

Humenik, F. J., M. R. Overcash, and L. B. Driggers. Swine production industry - waste characterization and management. 56 pp. Department of Biological and Agricultural Engineering, North Carolina State University, Raleigh, N. C. 1973.

Swine Waste Management Alternatives. North Carolina Agricultural Extension Service Circular 569. Raleigh, N. C. September 1973.

Dairy Waste Management Alternatives. North Carolina Agricultural Extension Service Circular 568. Raleigh, N. C. September 1973.

Poultry Waste Management Alternatives. North Carolina Agricultural Extension Service Circular 570. Raleigh, N. C. September 1973.

Beef Cattle Waste Management Alternatives. North Carolina Agricultural Extension Service Circular 571. Raleigh, N. C. March 1974.

Regulatory Criteria for Animal Waste Management. North Carolina Agricultural Extension Service Leaflet 191. Raleigh, N. C. May 1974.

Overcash, M. R. Economics of alternative wastewater treatment systems. Proceedings Workshop on Land Disposal of Wastewaters. Report No. 91. pp 69-74. Raleigh, N. C. November 1973.

Humenik, F. J. Agricultural Waste Management Techniques. Treatment systems for animal, agricultural, and municipal wastes. Proceedings Workshop on Land Disposal of Wastewaters. Water Resources

Research Institute of the University of North Carolina. Report No. 91. pp 91-104. Raleigh, N. C. November 1973.

Humenik, F. J. Effect of effluent discharge guidelines on the producer. Proceedings North Carolina Irrigation Conference. pp 11-20. Raleigh, N. C. November 1973.

Overcash, M. R. Research to comply economically with environmental guidelines. Proceedings North Carolina Irrigation Conference. pp 21-32. Raleigh, N. C. November 1973.

Humenik, F. J. New developments in swine waste management. Proceedings from Virginia Pork Industry Conference. pp 1-14. Sandston, Virginia. December 1973.

Humenik, F. J., M. R. Overcash, L. B. Driggers, and G. J. Kriz. Cleaning the animal farm environment. Environmental Science and Technology 8(12):984-989. 1974.

Humenik, F. J. Animal waste as a source. Proceedings U.S. EPA and Extension Committee on Organizational Policy Workshop on Non-point Source Water Pollution Control. pp 113-123. Washington, D. C. September 1974.

Moore, J. A., M. R. Overcash, T. B. S. Prakasam. Animal waste sample preservation and preparation. ASAE Paper No. 74-4545. Chicago, Illinois. December 1974.

Overcash, M. R., D. L. Reddell, D. L. Gay, and A. G. Hashimoto. Chemical analyses. ASAE Paper No. 74-4546. Chicago, Illinois. December 1974.

Sneed, R. E., F. J. Humenik, and M. R. Overcash. Design considerations for land application waste treatment systems. ASAE Paper 74-2556. Chicago, Illinois. December 1974.

Howell, E. S., M. R. Overcash, and F. J. Humenik. Unaerated swine waste lagoon response to loading intensity and frequency. ASAE Paper 74-4514. Chicago, Illinois. December 1974.

Humenik, F. J. An overview of land application of agricultural waste in the Southeast. Proceedings North Carolina Irrigation Conference. pp 1-10. Charlotte, N. C. December 1974.

Humenik, F. J., and J. C. Barker. New developments in swine waste management. Proceedings North Carolina Pork Producers Conference. pp 24-27. January 1975.

Humenik, F. J. System design considerations - process. Proceedings Southeastern Workshop on Land Application of Municipal, Industrial, and Agricultural Wastewater. North Carolina Agricultural Extension Service and Agricultural Experiment Station; Water

Resources Research Institute of the University of North Carolina. pp 4.1-4.14. Raleigh, N. C. January 1975.

Humenik, F. J. Animal waste land application systems. Proceedings Sprinkler Irrigation Association, Atlanta, Georgia, February 1975.

Overcash, M. R. and F. J. Humenik. Concepts for pretreatment-land application for small municipal systems. Second National Conference on Complete Water Reuse. AICHE. Chicago, Illinois. May 1975.

Overcash, M. R. and F. J. Humenik. Agriculture related pretreatment land application systems. Second National Conference on Complete Water Reuse. AICHE. Chicago, Illinois. May 1975.

Axtell, R. C., D. H. Rutz, M. R. Overcash and F. J. Humenik. Mosquito production and control in animal waste lagoons. Third International Symposium on Livestock Wastes, Univ. of Ill., Amer. Soc. Agr. Eng., PROC - 257:15-18, 21. Managing Livestock Wastes.

Overcash, M. R., F. J. Humenik and L. B. Driggers. Swine production and waste management. State-of-the-Art, Managing Livestock Wastes, Proc. Third International Symposium on Livestock Wastes, Univ. of Ill., Amer. Soc. Agr. Eng., PROC - 257:154-159, 163. April 1975.

Humenik, F. J., R. E. Sneed, M. R. Overcash, J. C. Barker and G. D. Wetherill. Total waste management for a large swine production facility. Managing Livestock Wastes. Proc. Third International Symposium on Livestock Wastes, Univ. of Ill. Amer. Soc. Agr. Eng. PROC - 257:168-173, April 1975.

Cummings, G. A., J. C. Burns, R. E. Sneed, M. R. Overcash and F. J. Humenik. Plant and soil effects of swine lagoon effluent applied to coastal bermuda grass. Managing Livestock Wastes, Proc. Third International Symposium on Livestock Wastes, Univ. of Ill., Amer. Soc. Agr. Eng., PROC - 257:598-601, April 1975.

Humenik, F. J., M. R. Overcash and R. Miller. Surface aeration: design and performance for swine lagoons. Managing Livestock Wastes, Proc. Third International Symposium on Livestock Wastes, Univ. of Ill. Amer. Soc. Agr. Eng. PROC - 257:568-571, April 1975.

Howell, E. S. Design criteria for swine waste lagoons. Ph.D Thesis. North Carolina State University, Raleigh, N. C. In preparation.

Miller, T. D. Aeration of animal waste lagoons for odor control and stabilization. M.S. Thesis. North Carolina State University, Raleigh, N. C. In preparation.

Overcash, M. R., J. W. Gilliam, F. J. Humenik and P. W. Westerman. Lagoon pretreatment: selected heavy metal and cation removals. Submitted to J. Water Pollution Control Federation.

Overcash, M. R., E. S. Howell, F. J. Humenik and P. W. Westerman. Swine waste lagoon response to loading frequency and intensity. Submitted to Transactions ASAE.

SECTION X

APPENDICES

		Page No.
A1	Imhoff Cones - First Experiment	257
A2	Imhoff Cones - Second Experiment	266
A3	14-l Reactors - Mass Balance	275
B1	Pilot-Scale Lagoon Temperature Data-°C	279
B2	Odor Rating Sheet	280
B3	Typical Lagoon Profile Data Obtained with Curved Tube Technique	281
B4	Field Pilot-Scale Reactor Temperature, Dissolved Oxygen at Surface and Bulk Supernatant TOC	282
B5	Hydrogen Ion Concentration Data	283
C1	Soil Concentration Profiles	287

APPENDIX AI. IMHOFF CONES - FIRST EXPERIMENT

I. Reference loading rate, no sludge,
once per week loading frequency,
1NS1

	Parameter			
	TKN	TOC	COD	$o\text{-}PO_4\text{-}P$
A. Inputs				
1) Initial load				
Volume, liters	1	1	1	1
Concentration, mg/l	995	1,750	5,504	110
Amount, g	.995	1.75	5.5	.110
% of feed	121.0	44.8	39.9	48.0
% of total input	54.7	30.9	28.5	32.4
2) Feed				
Volume, liters	.450	.450	.450	.450
Concentration, mg/l	1,833	8,667	30,612	510
Amount, g	.825	3.9	13.78	.229
% of feed	100	100	100	100
% of total input	45.3	69.1	71.5	67.6
B. Outputs				
1) Samples				
Volume, liters	.450	.450	.450	.450
Concentration, mg/l	424	931	2,055	67
Amount, g	.191	.419	.925	.030
% of feed	23.2	10.7	6.7	13.1
% of total input	10.5	7.4	4.8	8.8
2) Drained Sludge				
Volume, liters	.353	.353	.353	.353
Concentration, mg/l	1,020	8,754	22,776	637
Amount, g	.360	3.09	8.04	.225
% of feed	43.6	79.2	58.3	98.3
% of total input	19.8	54.7	41.7	66.4
C. Accumulation				
1) Final Supernatant				
Volume, liters	.670	.670	.670	.670
Concentration, mg/l	225	781	1,251	97
Amount, g	.151	.523	.838	.065
% of feed	18.3	13.4	6.09	28.4
% of total input	8.3	9.3	4.3	19.2

APPENDIX A1 (Continued)

	Parameter			
	TKN	TOC	$\bar{C}OD$	$o\text{-}PO_4\text{-}P$
2) Final Cleanout of Walls				
Volume, liters	1	1	1	1
Concentration, mg/l	63	460	1,117	45
Amount, g	.063	.460	1.12	.045
% of feed	7.6	11.2	8.1	19.6
% of total input	3.5	8.1	5.8	13.3
II. Reference loading rate, controlled sludge level, once per week loading frequency, RCS1				
A. Inputs				
1) Initial load				
(a) Supernatant				
Volume, liters	.990	.990	.990	.990
Conc., mg/l	995	1,750	5,504	110
Amount, g	.985	1.733	5.449	.109
% of feed	119.4	44.4	39.5	47.6
% of total input	53.5	30.0	27.7	32.1
(b) Sludge				
Volume, liters	.010	.010	.010	.010
Conc., mg/l	3,200	14,500	46,900	200
Amount, g	.032	.145	.469	.002
% of feed	3.9	3.7	3.4	.87
% of total input	1.7	2.5	2.4	.59
2) Feed				
Volume, liters	.450	.450	.450	.450
Concentration, mg/l	1,833	8,667	30,612	510
Amount, g	.825	3.9	13.78	.229
% of feed	100	100	100	100
% of total input	44.8	67.5	69.9	67.4
B. Outputs				
1) Samples				
Volume, liters	.500	.500	.500	.500
Concentration, mg/l	370	842	2,386	60
Amount, g	.185	.421	1.193	.030
% of feed	22.4	10.8	8.6	13.1
% of total input	10.0	7.3	6.1	8.8

APPENDIX A1 (Continued)

	Parameter			
	TKN	TOC	COD	o-PO$_4$-P
2) Drained sludge				
Volume, liters	.181	.181	.181	.181
Concentration, mg/l	1,564	10,867	40,840	1,337
Amount, g	.283	1.967	7.392	.242
% of feed	34.3	50.4	53.6	105.6
% of total input	15.4	34.0	37.5	71.2
C. Accummulation				
1) Final supernatant				
Volume, liters	.735	.735	.735	.735
Concentration, mg/l	148	484	1,687	67
Amount, g	.109	.356	1.240	.049
% of feed	13.2	9.1	9.0	21.4
% of total input	5.9	6.2	6.3	14.4
2) Final cleanout of walls, etc.				
Volume, liters	1	1	1	1
Concentration, mg/l	104	780	1,563	77
Amount, g	.104	.780	1.563	.077
% of feed	12.6	20.0	11.3	33.6
% of total input	5.6	13.5	7.9	22.6
III. Reference loading rate, accumulated sludge, once per week loading frequency, 1AS1				
A. Inputs				
1) Initial load				
(a) Supernatant				
Volume, liters	.990	.990	.990	.990
Conc., mg/l	995	1,750	5,504	110
Amount, g	.985	1.733	5.449	.109
% of feed	119.4	44.4	39.5	47.6
% of total input	53.5	30.0	27.7	32.1
(b) Sludge				
Volume, liters	.010	.010	.010	.010
Conc., mg/l	3,200	14,500	46,900	200
Amount, g	.032	.145	.469	.002
% of feed	3.9	3.7	3.4	.87
% of total input	1.7	2.5	2.4	.59

APPENDIX A1 (Continued)

	Parameter			
	TKN	TOC	COD	o-PO_4-P
2) Sludge				
Volume, liters	.450	.450	.450	.450
Concentration, mg/l	1,833	8,667	30,612	510
Amount, g	.825	3.9	13.78	.229
% of feed	100	100	100	100
% of total input	44.8	67.5	69.9	67.4
B. Outputs				
1) Samples				
Volume, liters	.580	.580	.580	.580
Concentration, mg/l	417	819	2,298	62
Amount, g	.242	.475	1.333	.036
% of feed	29.3	12.2	9.7	15.7
% of total input	13.1	8.2	6.7	10.6
C. Accumulation				
1) Final sludge				
Volume, liters	.105	.105	.105	.105
Concentration, mg/l	1,962	14,800	38,676	2,180
Amount, g	.206	1.554	4.061	.229
% of feed	25.0	39.8	29.5	100.0
% of total input	11.2	26.9	20.6	67.4
2) Final supernatant				
Volume, liters	.650	.650	.650	.650
Concentration, mg/l	157	720	1,442	85
Amount, g	.102	.468	.937	.055
% of feed	12.4	12.0	6.8	24.0
% of total input	5.5	8.1	4.8	16.2
3) Final Cleanout of walls, etc.				
Volume, liters	1	1	1	1
Concentration, mg/l	125	860	2,207	115
Amount, g	.125	.860	2.207	.115
% of feed	15.2	22.1	16.0	50.2
% of total input	6.8	14.9	11.2	33.8

APPENDIX A1 (Continued)

	Parameter			
	TKN	TOC	COD	$o\text{-}PO_4\text{-}P$
IV. Reference loading rate, no sludge, 3 times per week loading frequency, 1NS3				
A. Inputs				
1) Initial load				
(a) Supernatant				
Volume, liters	1	1	1	1
Conc., mg/l	995	1,750	5,504	110
Amount, g	.995	1.75	5.5	.110
% of feed	121.0	44.8	39.9	48.0
% of total input	54.7	30.9	28.5	32.4
2) Feed				
Volume, liters	.450	.450	.450	.450
Concentration, mg/l	1,833	8,667	30,612	510
Amount, g	.825	3.9	13.78	.229
% of feed	100	100	100	100
% of total input	45.3	69.1	71.5	67.6
B. Outputs				
1) Samples				
Volume, liters	.780	.780	.780	.780
Concentration, mg/l	506	669	1,963	44
Amount, g	.395	.522	1.531	.034
% of feed	47.9	13.4	11.1	14.8
% of total input	21.7	9.2	7.9	10.0
2) Drained sludge				
Volume, liters	.492	.492	.492	.492
Concentration, mg/l	1,000	6,262	19,041	612
Amount, g	.492	3.081	9.368	.301
% of feed	59.6	79.0	68.0	131.4
% of total input	27.0	54.5	48.6	88.8
C. Accumulation				
1) Final Supernatant				
Volume, liters	.295	.295	.295	.295
Concentration, mg/l	140	675	2,437	54
Amount, g	.041	.199	.719	.016
% of feed	5.0	5.1	5.2	7.0
% of total input	2.3	3.5	3.7	4.7

APPENDIX A1 (Continued)

	Parameter			
	TKN	TOC	COD	o-PO_4-P
2) Final cleanout of walls, etc.				
Volume, liters	1	1	1	1
Concentration, mg/l	40	100	360	40
Amount, g	.040	.100	.360	.040
% of feed	4.8	2.6	2.6	17.5
% of total input	2.2	1.8	1.9	11.8

V. Reference loading rate, controlled sludge level,
3 times per week loading frequency
1CS3

A. Inputs

	TKN	TOC	COD	o-PO_4-P
1) Initial load				
(a) Supernatant				
Volume, liters	.990	.990	.990	.990
Conc., mg/l	995	1,750	5,504	110
Amount, g	.985	.1733	5.449	.109
% of feed	119.4	44.4	39.5	32.1
% of total input	53.5	30.0	27.7	32.1
(b) Sludge				
Volume, liters	.010	.010	.010	.010
Conc., mg/l	3,200	14,500	46,900	200
Amount, g	.032	.145	.469	.002
% of feed	3.9	3.7	3.4	.87
% of total input	1.7	2.5	2.4	.59
2) Feed				
Volume, liters	.450	.450	.450	.450
Concentration, mg/l	1,833	8,667	30,612	510
Amount, g	.825	3.9	13.78	.229
% of feed	100	100	100	100
% of total input	44.8	67.5	69.9	67.4

APPENDIX A1 (Continued)

	Parameter			
	TKN	TOC	COD	o-PO_4-P
B. Outputs				
1) Samples				
Volume, liters	.580	.580	.580	.580
Concentration, mg/l	731	855	2,391	71
Amount, g	.424	.496	1.387	.041
% of feed	51.4	12.7	10.1	17.9
% of total input	23.0	8.6	7.0	12.1
2) Drained sludge				
Volume, liters	.158	.158	.158	.158
Concentration, mg/l	1,924	12,405	39,861	1,367
Amount, g	.304	1.960	6.298	.216
% of feed	36.8	50.3	45.7	94.3
% of total input	16.5	33.9	32.0	63.5
C. Accumulation				
1) Final supernatant				
Volume, liters	.708	.708	.708	.708
Concentration, mg/l	68	705	1,938	25
Amount, g	.048	.499	1.372	.018
% of feed	5.8	12.8	10.0	7.9
% of total input	2.6	7.8	6.9	5.3
2) Final cleanout of walls, etc.				
Volume, liters	1	1	1	1
Concentration, mg/l	88	600	1,446	78
Amount, g	.088	.600	1.446	.078
% of feed	10.7	15.4	10.5	34.1
% of total input	4.8	10.4	7.3	22.9
VI. Reference loading rate, accumulated sludge, 3 times per week loading rate, 1AS3				
A. Inputs				
1) Initial load				
(a) Supernatant				
Volume, liters	.990	.990	.990	.990
Conc., mg/l	995	1,750	5,504	110
Amount, g	.985	1.733	5.449	.109
% of feed	119.4	44.4	39.5	47.6
% of total input	53.4	30.0	27.7	32.1

APPENDIX A1 (Continued)

	Parameter			
	TKN	TOC	COD	o-PO_4-P
(b) Sludge				
Volume, liters	.010	.010	.010	.010
Conc., mg/l	3,200	14,500	46,900	200
Amount, g	.032	.145	.469	.002
% of feed	3.9	3.7	3.4	.87
% of total input	1.7	2.5	2.4	.59
2) Feed				
Volume, liters	.450	.450	.450	.450
Concentration, mg/l	1,833	8,667	30,612	510
Amount, g	.825	3.9	13.78	.229
% of feed	100	100	100	100
% of total input	44.8	67.5	69.9	67.4
B. Outputs				
1) Samples				
Volume, liters	.800	.800	.800	.800
Concentration, mg/l	498	598	1,951	45
Amount, g	.398	.478	1.561	.036
% of feed	48.2	12.3	11.3	15.7
% of total input	21.6	8.3	7.9	10.6
C. Accumulation				
1) Final Sludge				
Volume, liters	.100	.100	.100	.100
Concentration, mg/l	2,270	16,500	48,440	2,200
Amount, g	.227	1.650	4.844	.220
% of feed	27.5	42.3	35.2	96.1
% of total input	12.3	28.6	24.6	64.7
2) Final Supernatant				
Volume, liters	.548	.548	.548	.548
Concentration, mg/l	159	541	1,411	135
Amount, g	.087	.351	.773	.074
% of feed	10.5	9.0	5.6	32.3
% of total input	4.7	6.1	3.9	21.7

APPENDIX A1 (Continued)

	Parameter			
	TKN	TOC	COD	o-PO_4-P
3) Final cleanout of walls, etc.				
Volume, liters	1	1	1	1
Concentration, mg/l	105	740	1,660	83
Amount, g	.105	.740	1.660	.083
% of feed	12.7	18.9	12.0	36.2
% of total input	5.7	12.8	8.4	24.4

APPENDIX A2. IMHOFF CONES - SECOND EXPERIMENT

		Parameter	
	TKN	TOC	COD
I. Reference loading rate, no sludge, once per week loading frequency, 1NS1			
A. Inputs			
1) Initial load			
(a) Supernatant			
Volume, liters	1	1	1
Concentration, mg/l	0	0	0
Amount, g	0	0	0
% of feed	0	0	0
% of total input	0	0	0
2) Feed			
Volume, liters	.725	.725	.725
Concentration, mg/l	2,812	12,604	40,189
Amount, g	2.039	9.138	29.137
% of feed	100	100	100
% of total input	100	100	100
B. Outputs			
1) Samples			
Volume, liters	.580	.580	.580
Concentration, mg/l	138	305	734
Amount, g	.080	.177	.425
% of feed	3.9	1.9	1.5
% of total input	3.9	1.9	1.5
2) Drained Sludge			
Volume, liters	.466	.466	.466
Concentration, mg/l	1,178	5,981	22,172
Amount, g	.549	2.787	10.332
% of feed	26.9	30.5	35.5
% of total input	26.9	30.5	35.5
C. Accumulation			
1) Final Supernatant			
Volume, liters	.810	.810	.810
Concentration, mg/l	81	420	894
Amount, g	.066	.340	.724
% of feed	3.2	3.7	2.5
% of total input	3.2	3.7	2.5

APPENDIX A2 (Continued)

		Parameter	
	TKN	TOC	COD
II. Reference loading rate, controlled sludge level, once per week loading frequency, 1CS1			
A. Inputs			
1) Initial load			
(a) Supernatant			
Volume, liters	1	1	1
Concentration, mg/l	0	0	0
Amount, g	0	0	0
% of feed	0	0	0
% of total input	0	0	0
(b) Sludge			
Volume, liters	0	0	0
Concentration, mg/l	0	0	0
Amount, g	0	0	0
% of feed	0	0	0
% of total input	0	0	0
2) Feed			
Volume, liters	.725	.725	.725
Concentration, mg/l	2,812	12,604	40,189
Amount, g	2.039	9.138	29.137
% of feed	100	100	100
% of total input	100	100	100
B. Outputs			
1) Samples			
Volume, liters	.560	.560	.560
Concentration, mg/l	202	363	859
Amount, g	.113	.203	.481
% of feed	5.5	2.2	1.6
% of total input	5.5	2.2	1.6

APPENDIX A2 (Continued)

		Parameter	
	TKN	TOC	o-PO$_4$-P
C. Accumulation			
1) Sludge			
Volume, liters	.160	.160	.160
Concentration, mg/l	1,750	12,119	35,106
Amount, g	.280	1.939	5.617
% of feed	13.7	21.2	19.3
% of total input	13.7	21.2	19.3
2) Final supernatant			
Volume, liters	.845	.845	.845
Concentration, mg/l	134	705	1,215
Amount, g	.113	.596	1.027
% of feed	5.5	6.2	3.5
% of total input	5.5	6.2	3.5
3) Final cleanout of walls, etc.			
Volume, liters	1	1	1
Concentration, mg/l	137	1,350	3,294
Amount, g	.137	1.350	3.294
% of feed	6.7	14.8	11.3
% of total input	6.7	14.8	11.3
III. Reference loading rate, accumulated sludge, once per week loading frequency, 1AS1			
A. Inputs			
1) Initial load			
(a) Supernatant			
Volume, liters	1	1	1
Concentration, mg/l	0	0	0
Amount, g	0	0	0
% of feed	0	0	0
% of total input	0	0	0

APPENDIX A2 (Continued)

	Parameter		
	TKN	TOC	o-PO_4-P
(b) Sludge			
Volume, liters	0	0	0
Concentration, mg/l	0	0	0
Amount, g	0	0	0
% of feed	0	0	0
% of total input	0	0	0
2) Feed			
Volume, liters	.600	.600	.600
Concentration, mg/l	2,820	13,093	40,765
Amount, g	1.692	7.856	24.459
% of feed	100	100	100
% of total input	100	100	100
B. Outputs			
1) Samples			
Volume, liters	.460	.460	.460
Concentration, mg/l	191	341	852
Amount, g	.088	.157	.392
% of feed	5.2	2.0	1.6
% of total input	5.2	2.0	1.6
C. Accumulation			
1) Final Sludge			
Volume, liters	.147	.147	.147
Concentration, mg/l	2,084	10,465	36,227
Amount, g	.306	1.538	5.325
% of feed	18.1	19.6	21.8
% of total input	18.1	19.6	21.8
2) Final Supernatant			
Volume, liters	.700	.700	.700
Concentration, mg/l	232	445	1,402
Amount, g	.163	.312	.981
% of feed	9.6	4.0	4.0
% of total input	9.6	4.0	4.0

APPENDIX A2 (Continued)

		Parameter	
	TKN	TOC	COD
3) Final cleanout of walls, etc.			
Volume, liters	1	1	1
Concentration, mg/l	297	965	2,717
Amount, g	.297	.965	2.717
% of feed	17.6	12.3	11.1
% of total input	17.6	12.3	11.1

IV. 4 times reference loading rate, no sludge, once per week loading frequency, 4NS1

A. Inputs

	TKN	TOC	COD
1) Initial load			
(a) Supernatant			
Volume, liters	1	1	1
Concentration, mg/l	0	0	0
Amount, g	0	0	0
% of feed	0	0	0
% of total input	0	0	0
2) Feed			
Volume, liters	1.6	1.6	1.6
Concentration, mg/l	2,624	14,826	37,243
Amount, g	4.198	23.722	59.589
% of feed	100	100	100
% of total input	100	100	100

B. Outputs

	TKN	TOC	COD
1) Samples			
Volume, liters	.300	.300	.300
Concentration, mg/l	670	760	1,697
Amount, g	.201	.228	.509
% of feed	4.8	.96	.85
% of total input	4.8	.96	.85

APPENDIX A2 (Continued)

	Parameter		
	TKN	TOC	COD
2) Drained sludge			
Volume, liters	.701	.701	.701
Concentration, mg/l	2,244	12,879	48,134
Amount, g	1.573	9.028	33.742
% of feed	37.5	38.1	56.6
% of total input	37.5	38.1	56.6
C. Accumulation			
1) Final supernatant			
Volume, liters	1	1	1
Concentration, mg/l	880	940	2,039
Amount, g	.880	.940	2.039
% of feed	20.9	4.0	3.4
% of total input	20.9	4.0	3.4
2) Final cleanout of walls, etc.			
Volume, liters	1	1	1
Concentration, mg/l	66	410	1,250
Amount, g	.066	.410	1.25
% of feed	1.6	1.7	2.1
% of total input	1.6	1.7	2.1

V. 4 times reference loading rate, controlled sludge level, once per week loading frequency, 4CS1

A. Inputs

	TKN	TOC	COD
1) Initial load			
(a) Supernatant			
Volume, liters	1	1	1
Concentration, mg/l	0	0	0
Amount, g	0	0	0
% of feed	0	0	0
% of total input	0	0	0

APPENDIX A2 (Continued)

	Parameter		
	TKN	TOC	COD
(b) Sludge			
Volume, liters	0	0	0
Concentration, mg/l	0	0	0
Amount, g	0	0	0
% of feed	0	0	0
% of total input	0	0	0
2) Feed			
Volume, liters	1.6	1.6	1.6
Concentration, mg/l	2,624	14,826	37,243
Amount, g	4.198	23.722	59.589
% of feed	100	100	100
% of total input	100	100	100
B. Outputs			
1) Samples			
Volume, liters	.320	.320	.320
Concentration, mg/l	665	747	1,847
Amount, g	.213	.239	.591
% of feed	5.07	1.0	.99
% of total input	5.07	1.0	.99
2) Drained sludge			
Volume, liters	.647	.647	.647
Concentration, mg/l	2,249	12,559	49,575
Amount, g	1.455	8.126	32.075
% of feed	34.6	34.3	53.8
% of total input	34.6	34.3	53.8
C. Accumulation			
1) Final supernatant			
Volume, liters	.940	.940	.940
Concentration, mg/l	1,036	1,110	3,061
Amount, g	.974	1.043	2.878
% of feed	23.2	4.4	4.8
% of total input	23.2	4.4	4.8

APPENDIX A2 (Continued)

	Parameter		
	TKN	TOC	COD
2) Final cleanout of walls, etc.			
Volume, liters	1	1	1
Concentration, mg/l	53	260	688
Amount, g	.053	.260	.688
% of feed	1.3	1.09	1.15
% of total input	1.3	1.09	1.15
3) Effluent			
Volume, liters	.500	.500	.500
Concentration, mg/l	684	802	1,826
Amount, g	.342	.401	.913
% of feed	8.1	1.7	1.5
% of total input	8.1	1.7	1.5

VI. 4 times reference loading rate, accumulated sludge,
once per week loading frequency,
4AS1

A. Inputs

	TKN	TOC	COD
1) Initial load			
(a) Supernatant			
Volume, liters	1	1	1
Concentration, mg/l	0	0	0
Amount, g	0	0	0
% of feed	0	0	0
% of total input	0	0	0
(b) Sludge			
Volume, liters	0	0	0
Concentration, mg/l	0	0	0
Amount, g	0	0	0
% of feed	0	0	0
% of total input	0	0	0
2) Feed			
Volume, liters	1.6	1.6	1.6
Concentration, mg/l	2,624	14,826	37,243
Amount, g	4.198	23.722	59.589
% of feed	100	100	100
% of total input	100	100	100

APPENDIX A2 (Continued)

		Parameter	
	TKN	TOC	COD
B. Outputs			
1) Samples			
Volume, liters	.320	.320	.320
Concentration, mg/l	847	834	2,034
Amount, g	.271	.267	.651
% of feed	6.5	1.1	1.1
% of total input	6.5	1.1	1.1
C. Accumulation			
1) Final sludge			
Volume, liters	.240	.240	.240
Concentration, mg/l	537	21,596	70,513
Amount, g	1.288	5.183	16.923
% of feed	30.7	21.8	28.4
% of total input	30.7	21.8	28.4
2) Final supernatant			
Volume, liters	.725	.725	.725
Concentration, mg/l	1,389	950	2,399
Amount, g	1.007	.689	1.739
% of feed	24.0	2.9	2.9
% of total input	24.0	2.9	2.9
3) Final cleanout of walls, etc.			
Volume, liters	1	1	1
Concentration, mg/l	109	210	734
Amount, g	.109	.210	.734
% of feed	2.6	.88	1.2
% of total input	2.6	.88	1.2
4) Effluent			
Volume, liters	1.025	1.025	1.025
Concentration, mg/l	599	588	1,408
Amount, g	.614	.603	1.444
% of feed	14.6	2.5	2.4
% of total input	14.6	2.5	2.4

APPENDIX A3. 14 1 REACTORS - MASS BALANCE

I. 1.2 times reference loading rate,
once per 2 weeks loading frequency

	Parameter			
	TKN	TOC	COD	o-PO_4-P
A. Inputs				
1) Initial load 14 1 liters of water				
2) Feed				
Volume, liters	25.54	25.54	25.54	25.54
Concentration, mg/1	2,323	11,052	33,574	713
Amount, g	59.328	282.26	857.48	18.199
% of feed	100	100	100	100
B. Outputs				
1) Samples				
Volume, liters	2.25	2.25	2.25	2.25
Concentration, mg/1	267	377	993	28
Amount, g	.600	.848	2.235	.063
% of feed	1.0	.30	.26	.35
C. Accumulation				
1) Final supernatant				
Volume, liters	11.487	11.487	11.487	11.487
Concentration, mg/1	419	680	2,402	28.5
Amount, g	4.813	7.811	27.592	.327
% of feed	8.1	2.7	3.2	1.8
2) Final sludge				
Volume, liters	2.513	2.513	2.513	2.513
Concentration, mg/1	2,914	28,618	98,982	1,800
Amount, g	7.325	71.917	248.741	4.523
% of feed	12.4	25.5	29.0	24.9
3) Final cleanout of walls, etc.				
Volume, liters	1	1	1	1
Concentration, mg/1	778	1,705	5,894	356
Amount, g	.778	1.705	5.894	.356
% of feed	1.3	.60	.69	1.9

APPENDIX A3 (Continued)

	Parameter			
	TKN	TOC	COD	o-PO$_4$-P
II. 1.2 times reference loading rate, once per week loading frequency				
A. Inputs				
1) Initial load 14 liters of water				
2) Feed				
Volume, liters	25.54	25.54	25.54	25.54
Concentration, mg/l	2,323	11,052	33,574	713
Amount, g	59.328	282.26	857.48	18.199
% of feed	100	100	100	100
B. Outputs				
1) Samples				
Volume, liters	3.65	3.65	3.65	3.65
Concentration, mg/l	261.4	372.3	1,075.7	27.6
Amount, g	.954	1.36	3.93	0.101
% of feed	1.6	.48	.46	.56
C. Accumulation				
1) Final supernatant				
Volume, liters	9.48	9.48	9.48	9.48
Concentration, mg/l	386	875	1,867	17.2
Amount, g	3.659	8.30	3.66	0.163
% of feed	6.2	2.9	0.43	0.89
2) Final sludge				
Volume, liters	2.299	2.299	2.299	2.299
Concentration, mg/l	3,826	26,465	99,508	3,150
Amount, g	8.796	60.843	228.769	7.242
% of feed	14.83	21.60	26.6	39.79
3) Final cleanout of walls, etc.				
Volume, liters	1	1	1	1
Concentration, mg/l	630	1,900	3,851	456
Amount, g	.630	1.900	3.851	.456
% of feed	1.1	.67	.45	2.5

APPENDIX A3 (Continued)

	Parameter			
	TKN	TOC	COD	$o\text{-}PO_4\text{-}P$
III. 1.2 times reference loading rate, two times per week loading frequency				
A. Inputs				
1) Initial load 14 liters of water				
2) Feed				
Volume, liters	25.54	25.54	25.54	25.54
Concentration, mg/l	2,323	11,052	33,574	713
Amount, g	59.328	282.26	857.48	18.199
% of feed	100	100	100	100
B. Outputs				
1) Samples				
Volume, liters	4.35	4.35	4.35	4.35
Concentration, mg/l	260.9	320.5	956.6	32.4
Amount, g	1.135	1.394	4.161	.141
% of feed	1.9	.49	.49	.77
C. Accumulation				
1) Final supernatant				
Volume, liters	10.526	10.526	10.526	10.526
Concentration, mg/l	378	780	1,781	22.8
Amount, g	3.979	8.210	18.747	.240
% of feed	6.7	2.9	2.2	1.3
2) Final sludge				
Volume, liters	2.299	2.299	2.299	2.299
Concentration, mg/l	3,391	31,137	111,475	1,980
Amount, g	7.796	71.583	256.281	4.552
% of feed	13.1	25.3	29.8	25.0
3) Final cleanout of walls, etc.				
Volume, liters	1	1	1	1
Concentration, mg/l	572	1,310	3,297	270
Amount, g	.572	1.310	3.297	.270
% of feed	.96	.46	.38	1.5

APPENDIX A3 (Continued)

	Parameter			
	TKN	TOC	COD	o-PO_4-P
IV. 1.2 times reference loading rate, three times per week loading frequency				
A. Inputs				
1) Initial load 14 liters of water				
2) Feed				
Volume, liters	25.54	25.54	25.54	25.54
Concentration, mg/l	2,323	11,052	33,574	713
Amount, g	59.328	28.226	857.48	18.199
% of feed	100	100	100	100
B. Outputs				
1) Samples				
Volume, liters	6.4	6.4	6.4	6.4
Concentration, mg/l	260.9	334.7	997.5	41.4
Amount, g	1.67	2.142	6.384	.265
% of feed	2.8	.76	.74	1.4
C. Accumulation				
1) Final Supernatant				
Volume, liters	10.540	10.540	10.540	10.540
Concentration, mg/l	406	845	1,914	26.0
Amount, g	4.274	8.894	20.147	.274
% of feed	7.2	3.2	2.3	1.5
2) Final sludge				
Volume, liters	2.168	2.168	2.168	2.168
Concentration, mg/l	3,473	27,577	79,695	2,130
Amount, g	7.529	59.787	176.343	4.618
% of feed	12.7	21.2	20.6	25.4
3) Final cleanout of walls, etc.				
Volume, liters	1	1	1	1
Concentration, mg/l	557	1,435	3,563	220
Amount, g	.557	1.435	3.563	.220
% of feed	.94	.51	.42	1.2

APPENDIX B1. PILOT SCALE LAGOON TEMPERATURE DATA-°C

Date	Loading Rate - Fraction of Reference Rate											
	4	1	1/16	1/32	4	1	1/16	1/32	4	1	1/16	1/32
	Top of Reactor				Middle of Reactor				Bottom of Reactor			
9/15/72	25	26	29	28.5	25	22	25.5	26	25	22	24	24.5
9/19/72	25.5	26	30.5	30	25	22.5	26	26	25	21.5	24	23
9/22/72	24	25	28	27	23	22	23	23	23	21	21.5	22.5
9/27/72	25	24	27.5	27.5	24	22	23.5	24.5	24	21.5	22	23.5
9/29/72	25	27	27.5	27	23.5	23.5	23.5	25.5	23.5	22	22.5	22.5
10/4/72	21.5	23	25	24	20	19.5	20	21.5	20	18.5	20	20.5
10/6/72	23.5	22.5	23	23	21	20	20	21.5	20	19.5	20	20.5
11/2/72	23	23	22.5	23	21	21	20	21	20	19.5	19	19
11/16/72	11	11	12.5	12	11	10.5	12.5	11	11	10.5	12.5	11
11/24/72	7	8.5	10	10.5	7.5	9	10	10.5	8.5	9	10	10.5
12/1/72	7.5	6.5	7.5	8	7	7	7.5	8	7	7	7	8
1/18/73	7	10.5	8.5	9	4	5	5	5	4	5	4.5	5
2/1/73	8	8	9	9	6	5.5	5.5	5.5	6	5	5	5
2/16/73	7	4.5	5	7	6	4.5	5	5	6	5	6	5
3/14/73	16.5	18	15	21	15	12	10	12	11	10	9	9
7/6/73	31	27.2	34	32.5	28	26	21.5	24	27	26	20	22
10/18/73	19	19	20	20	17	16	16.5	17.5	17	16	16.5	17
11/13/73			15.5	16			15	14.5			14.5	13.5
11/29/73			15.5	15			14.5	14			14	13.5
1/8/74	8	8	8	8.5	7.5	7	7.5	7	7	7	6.5	6.5
2/12/74			6.5	8								7
3/19/74	16	15	15.5	15	15.5	15	15	14.5	15	14.5	14.5	14
4/9/74	18	17.5	17	17.5	16	15.5	15	14.5	15	14.5	14	14
5/17/74			25	28.5			15.5	17			14.5	16
6/25/74	26.5	24	24	24.5	25.5	23.5	22.5	24	25	23.5	21.5	23
7/2/74	26	26	29	30	26	23.2	21.8	23.3	26	24	21	22
7/16/74	28.8	25.3	26.3	27	28.3	24.3	24	24	28	24.3	22.8	22.5
8/6/74	25.5	23	23	24	25	23.5	23	23.5	25	23.5	22	23.5
8/22/74	28	26.5	29.5	30.5	28	25.5	25	25	27.5	25.5	24	24.5
10/8/74	20	17	16	17	19.5	16	15.5	16.5	19	16	15.5	16.5
2/7/75	9	7.5	6.5	7	8	6.5	7	7	8	8	7	7

Appendix B2. ODOR RATING SHEET

Name______________________________________ Date__________________________

If you encountered this odor which one of the following would must closely describe your attitude?

1. Strongly object
2. Object
3. Would not object
4. Would not offend you at all

Lagoon designation	Description (1-4)

Appendix B3. TYPICAL LAGOON PROFILE DATA OBTAINED WITH CURVED TUBE TECHNIQUE

Lagoon	Position above bottom, m	Concentration, mg/l				
		COD	TOC	o-PO_4-P	TKN	NH_3-N
½	1.49	1,860	70	65	370	--
	1.18	1,800	180	56	360	--
	0.873	2,000	170	56	370	--
	0.565	1,700	250	53	360	--
	0.257	2,200	305	59	380	--
	0.206	2,800	285	65	780	--
	0.155	1,560	320	52	190	--
	0.104	1,500	305	52	350	--
	0.053	10,300	1,100	240	380	--
	0.	58,300	4,000	2,470	3,460	--
1	1.04	1,550	700	93	850	240
	0.924	1,740	750	109	760	840
	0.616	3,600	1,600	112	750	1,010
	0.536	5,400	2,560	290	790	4,330
	0.459	35,700	14,800	2,200	990	3,300
	0.308	41,500	16,800	701	1,060	3,570
	0.153	45,300	19,000	2,540	1,230	3,600
	0.076	43,500	18,200	2,400	1,620	3,500
	0.	42,400	16,200	2,750	950	3,900

APPENDIX B4. FIELD PILOT-SCALE REACTOR TEMPERATURE, DISSOLVED OXYGEN AT SURFACE AND BULK SUPERNATANT TOC

Date	Loading rate (fraction of reference rate)	Temperature °C	D.O mg/1	COD mg/1	TOC mg/1
10/18/73	1/16	20	15+	240	100
	3rd series lagoon	19.5	15+	340	140
	1/32	20	5.3	160	60
11/13/73	1/16	15.5	11.6	420	120
	3rd series lagoon	15	9.5	310	120
	1/32	16	15+	140	75
11/29/73	1/16	15.5	12.6	380	160
	3rd series lagoon	15	1.6	290	130
	1/32	15	6.4	200	90
1/8/74	1/16	8	7.6	350	160
	3rd series lagoon	9	3.4	490	160
	1/32	8.5	9.5	205	95
2/12/74	1/16	6.5	0	470	180
	3rd series lagoon	6	0	500	200
	1/32	8	1.3	235	75
3/19/74	1/16	15.5	13.6	500	180
	3rd series lagoon	16	8.6	580	240
	1/32	15	15	295	220
4/9/74	1/16	17	8.6	550	220
	3rd series lagoon	18	3.6	600	290
	1/32	17.5	11.9	390	160

Appendix B5. HYDROGEN ION CONCENTRATION DATA

Sample source	Multiple or fraction of reference loading	Date	pH
Pilot-scale reactors	4	3/23/73	7.30
	4	3/27/73	7.65
	4	4/3/73	7.60
	4	4/10/73	7.43
	4	4/17/73	7.49
	4	5/2/73	7.60
	4	5/15/73	7.75
	4	10/16/73	7.65
	4	10/19/73	7.80
	4	3/21/74	7.40
	1	3/23/73	7.49
	1	3/27/73	7.88
	1	4/3/73	7.67
	1	4/10/73	7.50
	1	4/17/73	7.63
	1	5/2/73	7.56
	1	5/15/73	8.02
	1	10/16/73	7.70
	1	10/19/73	7.70
	1	3/21/74	7.45
	1/2	3/23/73	7.57
	1/2	3/27/73	7.71
	1/2	4/3/73	7.98
	1/2	4/10/73	7.70
	1/2	4/17/73	7.70
	1/2	5/2/73	7.59
	1/2	5/15/73	7.53
	1/2	10/16/73	7.90
	1/2	10/19/73	7.75
	1/2	3/21/74	7.40
	1/4	3/23/73	7.45
	1/4	3/27/73	7.71
	1/4	4/3/73	7.55
	1/4	4/10/73	7.50
	1/4	4/17/73	7.48
	1/4	5/2/73	7.27
	1/4	5/15/73	7.27
	1/4	10/16/73	7.75
	1/4	10/19/73	7.65
	1/4	3/21/74	7.60

APPENDIX B5. (continued)

Sample source	Multiple or fraction of reference loading	Date	pH
Pilot-scale reactors	1/8	3/23/73	7.37
	1/8	3/27/73	7.24
	1/8	4/3/73	7.54
	1/8	4/10/73	7.18
	1/8	4/17/73	7.45
	1/8	5/2/73	7.23
	1/8	5/15/73	7.20
	1/8	10/16/73	7.80
	1/8	10/19/73	7.60
	1/8	3/21/74	7.90
	1/16	3/23/73	7.34
	1/16	3/27/73	7.12
	1/16	4/3/73	7.31
	1/16	4/10/73	7.18
	1/16	4/17/73	7.19
	1/16	5/2/73	7.00
	1/16	5/15/73	6.91
	1/16	10/16/73	7.85
	1/16	10/19/73	7.70
	1/16	3/21/74	7.40
	1/16	3/23/73	7.34
	1/16	3/27/73	7.12
	1/16	4/3/73	7.31
	1/16	4/10/73	7.18
	1/16	4/17/73	7.19
	1/16	5/2/73	7.00
	1/16	5/15/73	6.91
	1/16	10/16/73	7.85
	1/16	10/19/73	7.70
	1/16	3/21/74	7.80
	1/32	3/23/73	7.38
	1/32	3/27/73	7.10
	1/32	4/3/73	7.00
	1/32	4/10/73	6.71
	1/32	4/17/73	7.06
	1/32	5/2/73	6.46
	1/32	7/15/73	6.80
	1/32	10/16/73	7.55
	1/32	10/19/73	7.30
	1/32	3/21/74	8.40
	1A	3/23/73	7.60
	1A	3/27/73	7.90
	1A	4/3/73	7.65
	1A	4/10/73	7.76
	1A	4/17/73	7.62

APPENDIX B5. (continued)

Sample source	Multiple or fraction of reference loading	Date	pH
Pilot-scale reactors	1A	5/2/73	7.70
	1A	5/15/73	7.52
	1A	10/16/73	8.00
	1A	10/19/73	7.95
	1A	3/21/74	8.10
	1B	3/23/73	7.70
	1B	3/27/73	7.58
	1B	4/3/73	7.70
	1B	4/10/73	7.39
	1B	4/17/73	7.60
	1B	5/2/73	7.50
	1B	5/15/73	7.40
	1B	10/16/73	8.40
	1B	10/19/73	8.30
	1B	3/21/74	8.40
Lab reactors	1.2	3/23/73	7.63
	1.2	4/5/73	7.59
	1.2	4/11/73	8.31
	1.2	4/18/73	8.32
	1.2	5/2/73	8.26
	1.2	5/16/73	8.18
	1.2	3/23/73	7.83
	1.2	4/5/73	8.00
	1.2	4/10/73	8.48
	1.2	4/17/73	8.36
	1.2	5/1/73	8.23
	1.2	5/16/73	8.18
	1.2	3/23/73	8.00
	1.2	4/5/73	7.96
	1.2	4/11/73	8.37
	1.2	4/18/73	8.21
	1.2	5/2/73	8.06
	1.2	5/16/73	8.31
	1.2	3/23/73	7.56
	1.2	4/5/73	7.45
	1.2	4/11/73	8.13
	1.2	4/18/73	8.01
	1.2	5/2/73	7.91
	1.2	5/16/73	8.12
Raw waste		3/20/73	7.43
		3/22/73	7.78
		2/22/73	7.20
		4/3/73	7.62

APPENDIX B5. (continued)

Sample source	Multiple or fraction of reference loading	Date	pH
Raw waste		4/17/73	7.68
		5/2/73	7.63
		5/15/73	7.46

APPENDIX C1. SOIL CONCENTRATION PROFILES

Total Kjeldahl Nitrogen (TKN), ppm

Depth, cm	September, 1973 Plot									March, 1974 Plot								
	1-H	2-L	3-M	4-H	5-M	6-L	7-H	8-L	9-M	1-H	2-L	3-M	4-H	5-M	6-L	7-H	8-L	9-M
0- 5	484	441	288	326	188	231	439	534	388	280	390	450	390	390	220	530	480	420
5-10	348	625	377	237	273	156	467	391	478	280	360	280	310	220	250	450	500	390
10-15	288	374	231	182	245	175	367	290	296	280	360	220	280	220	250	340	390	280
15-20	290	364	205	245	364	224	139	205	147	340	310	200	250	200	220	200	250	220
20-25	265	210	205	182	186	216	151	228	147	480	360	310	250	200	200	220	280	220
25-35	312	168	276	276	101	151	147	161	153	220	200	220	140	200	170	250	250	200
35-45	272	120	154	133	105	95	209	119	216	170	200	200	140	110	140	280	220	140
45-55	294	87	123	213	102	41	151	146	150	140	110	140	140	110	140	310	220	310
55-65	234	98	158	140	78	102	142	104	64	170	110	200	110	110	110	220	220	280
65-75	248	107	66	186	136	136	-	103	-	360	200	200	220	220	140	360	220	230

Nitrate-Nitrogen (NO_3-N), ppm

Depth, cm	September, 1973 Plot									December, 1973 Plot								
0- 5	5.1	.8	.8	4.0	.5	.9	2.8	1.8	.9	1.7	.8	1.3	2.2	1.0	1.0	1.2	.1	0
5-10	1.9	1.0	.7	3.0	.9	.7	3.2	1.5	.5	1.3	.6	1.0	.9	.8	.5	.6	.1	0
10-15	2.8	.3	.6	2.1	.5	.4	4.4	1.2	1.2	1.2	.6	.6	.8	.6	.5	.6	1.2	0
15-20	5.1	.2	.3	2.1	.5	.4	6.9	1.4	1.5	1.0	.6	.9	.9	.9	.5	1.5	.1	0
20-25	8.0	.6	.5	2.4	.4	.7	5.8	1.0	.9	1.2	.6	.9	1.0	.8	.5	1.0	0	0
25-35	10.2	.8	.8	4.6	.8	.5	7.4	1.2	1.5	1.3	.8	1.0	1.2	.6	.5	1.6	0	.6
35-45	8.5	1.9	.7	3.9	1.3	1.2	4.6	.6	2.9	1.0	.8	1.0	1.0	.6	.4	1.7	0	.5
45-55	13.1	.9	.8	4.4	.8	.6	6.5	.8	2.4	1.7	1.0	1.2	1.2	.8	.5	1.7	0	.3
55-65	11.0	3.5	.7	8.0	.7	.7	3.0	1.0	1.9	2.5	.8	1.7	1.4	.8	.4	3.1	0	.4
65-75	14.0	1.3	.5	7.8	.6	.9	3.5	.9	1.6	4.8	2.1	2.5	4.2	2.3	.5	2.3	1.3	.3

Calcium (Ca), ppm

Depth, cm	September, 1973 Plot									December, 1973 Plot								
0- 5	254	209	251	247	179	182	194	161	189	199	165	169	184	186	238	155	117	174
5-10	206	205	206	155	123	87	150	101	127	138	173	127	130	101	201	102	131	91
10-15	98	107	115	85	91	60	57	42	51	93	121	88	69	82	90	43	28	28
15-20	75	121	80	82	69	54	21	30	26	59	73	83	53	54	43	22	27	27
20-25	44	85	61	62	79	50	16	45	28	38	60	97	40	47	46	26	46	22
25-35	29	40	41	28	39	41	22	37	28	26	67	65	31	67	31	50	51	40
35-45	27	22	39	34	34	28	57	26	52	33	41	39	46	31	35	80	63	61
45-55	30	21	32	17	19	24	87	25	82	20	18	22	27	20	17	71	58	65
55-65	35	20	46	45	20	16	61	29	88	20	22	34	35	20	29	67	61	84
65-75	43	26	63	69	29	40	62	44	68	25	30	38	52	31	23	59	37	81

APPENDIX C1. (continued)

Sodium (Na), ppm

Depth, cm	September, 1973									December, 1973								
	1-H	2-L	3-M	4-H	5-M	6-L	7-M	8-L	9-M	1-H	2-L	3-M	4-H	5-M	6-L	7-M	8-L	9-M
0-5	8	6	10	9	7	5	10	9	10	16	9	2	6	4	9	14	17	8
5-10	9	8	13	10	11	6	12	19	14	9	10	3	6	4	9	13	23	11
10-15	13	7	15	9	13	10	11	10	10	9	13	3	10	9	11	15	11	12
15-20	10	8	17	9	13	8	9	9	11	12	10	7	13	10	11	15	10	17
20-25	11	7	15	10	10	4	7	10	10	9	11	11	9	10	13	19	12	29
25-35	9	6	12	10	9	7	12	7	11	7	10	11	11	12	9	31	15	19
35-45	8	6	9	9	8	4	16	6	14	6	7	9	12	9	10	48	22	25
45-55	9	7	6	8	8	4	15	4	21	8	7	7	12	9	8	34	18	31
55-65	10	5	9	12	7	4	9	4	19	8	6	15	19	10	17	28	26	30
65-75	12	6	11	15	7	7	14	6	12	12	16	22	31	15	11	34	14	22

Copper (Cu), ppm

Depth, cm	September, 1973									December, 1973								
0-5	1.8	1.2	1.2	1.1	2.4	1.10	1.1	1.2	1.4	3.2	1.4	1.5	1.7	1.3	7.6	1.0	.8	1.3
5-10	1.4	.7	1.1	1.1	1.1	1.1	1.1	1.3	1.2	8.	1.2	1.	1.0	1.1	3.2	1.0	1.2	1.1
10-15	1.0	1.6	.9	1.6	2.9	.9	1.4	.9	.9	3.0	1.0	1.	.8	.9	.9	2.2	1.1	1.1
15-20	.9	1.0	1.6	1.8	.6	.8	1.1	1.4	1.4	3.0	.9	1.	1.1	.7	.9	1.3	1.0	1.3
20-25	1.4	1.2	2.1	1.4	1.1	.6	1.5	1.1	1.1	4.0	.8	1.	.8	1.1	.7	1.1	1.0	1.5
25-35	2.1	1.3	1.1	1.4	.9	.9	.9	2.5	2.1	2.2	.9	.7	.7	.7	.4	.8	.7	.7
35-45	1.1	1.0	1.8	1.4	1.1	.9	.9	1.0	.9	2.0	.8	.7	.7	.9	.6	.9	.6	.7
45-55	1.4	.9	2.5	1.5	1.5	.6	.9	1.3	.9	1.5	.9	.6	.7	.7	.7	.7	.6	.6
55-65	1.8	.8	3.8	2.9	1.6	.5	1.3	1.4	1.8	1.2	.8	.9	.8	.7	.7	.8	.8	.7
65-75	1.4	1.4	.9	1.9	10.3	1.5	1.6	2.0	1.4	1.8	1.2	.8	.8	.6	.4	1.2	.8	.7

Zinc (Zn), ppm

Depth, cm	September, 1973									December, 1973								
0-5	5.2	1.6	1.9	3.0	4.9	1.6	2.6	1.9	1.8	7.3	3.7	4.6	3.3	4.2	5.9	3.2	2.6	4.0
5-10	1.3	1.6	2.3	2.0	2.2	.9	1.5	1.6	1.9	7.3	5.6	2.4	2.8	1.9	3.9	2.8	2.9	2.3
10-15	1.8	1.2	2.6	.9	2.3	.7	1.5	3.6	2.0	7.3	3.3	1.9	2.9	2.0	2.3	2.8	2.2	1.9
15-20	.9	1.4	1.1	1.1	2.0	3.6	1.0	1.1	2.0	10.7	2.5	2.3	2.0	1.9	2.0	3.1	2.0	2.5
20-25	1.3	1.3	6.0	1.6	2.0	.6	1.1	1.3	2.6	6.6	3.9	2.9	2.6	2.1	2.9	2.2	2.8	2.0
25-35	7.3	1.4	1.0	1.1	.7	.9	2.2	2.6	1.6	2.9	3.3	1.5	1.6	1.7	1.2	1.3	2.0	1.9
35-45	.8	1.1	1.5	1.3	2.9	.6	3.5	1.7	1.2	2.8	2.7	2.4	1.6	1.2	1.9	1.7	1.5	3.4
45-55	1.1	2.4	1.9	1.2	1.0	2.1	2.1	2.8	7.7	4.1	1.3	2.8	1.5	1.7	1.1	1.1	1.1	4.2
55-65	19.1	1.5	2.3	2.0	1.1	2.6	2.0	1.3	1.1	4.6	1.2	1.8	1.9	1.3	1.1	1.6	1.8	2.6
65-75	1.3	1.3	1.7	.9	5.1	3.0	1.4	1.5	3.6	2.0	2.1	1.6	2.5	1.6	1.6	1.5	1.9	1.4

APPENDIX C1. (continued)

Iron (Fe), ppm

Depth, cm	September, 1973									December, 1973								
	1-H	2-L	3-M	4-H	5-M	6-L	7-H	8-L	9-M	1-H	2-L	3-M	4-H	5-M	6-L	7-H	8-L	9-M
0-5	51	35	36	38	39	29	46	33	36	66	43	38	55	52	59	80	66	73
5-10	37	34	34	31	31	26	36	28	36	69	57	48	46	49	55	60	58	51
10-15	32	33	28	25	36	26	29	27	29	67	56	53	57	41	49	63	48	59
15-20	26	37	38	29	30	35	25	32	19	56	50	48	47	45	46	52	47	60
20-25	36	28	30	29	28	29	24	30	18	63	52	36	54	39	51	62	46	58
25-35	18	24	21	21	25	19	19	27	25	37	37	39	36	39	35	38	37	41
35-45	18	15	23	14	16	19	37	25	7	36	38	31	41	30	31	38	32	40
45-55	13	8	20	12	14	13	33	29	26	30	28	20	30	28	24	41	32	39
55-65	19	15	22	18	19	9	33	19	27	20	24	14	31	30	34	38	46	30
65-75	15	19	38	21	23	20	18	24	22	23	27	30	35	29	30	56	29	40

Manganese (Mn), ppm

Depth, cm	September, 1973									December, 1973								
0-5	9.6	11.6	11.0	8.5	7.1	5.4	10.9	12.3	11.9	9.5	10.6	6.6	7.2	7.0	5.9	9.8	11.5	10.8
5-10	8.8	11.4	9.3	6.6	5.6	3.1	9.4	12.5	10.9	9.6	22.8	8.0	5.9	5.1	6.2	9.2	9.2	13.5
10-15	11.8	11.1	8.1	4.7	6.4	4.3	6.9	9.9	9.1	9.4	11.8	9.2	6.7	5.9	4.5	7.7	7.9	7.0
15-20	6.1	11.2	7.2	6.4	4.8	4.6	8.5	10.9	4.9	9.1	9.1	10.2	5.7	5.1	3.0	5.0	5.5	8.4
20-25	5.5	8.3	5.5	5.2	5.7	3.2	2.9	14.5	1.9	6.8	9.7	6.8	5.2	2.5	3.7	2.7	4.3	4.4
25-35	2.3	4.7	4.0	2.3	2.9	2.5	1.6	17.8	1.5	3.4	5.1	5.1	2.4	3.7	1.8	1.7	2.3	3.9
35-45	1.8	2.2	1.7	1.5	1.3	1.9	2.1	3.0	1.8	2.8	3.2	3.4	2.5	2.0	1.7	1.9	1.9	2.9
45-55	1.8	1.4	1.0	1.1	1.1	1.2	1.6	1.3	1.5	2.0	1.5	1.4	1.5	1.6	1.1	1.7	1.4	1.7
55-65	2.3	1.6	1.1	1.7	.8	1.2	1.6	.8	1.2	1.2	1.7	1.2	1.5	1.3	1.1	1.6	1.6	1.8
65-75	1.2	1.0	1.5	1.2	.9	1.7	1.3	1.4	1.3	1.8	1.1	1.5	2.0	1.3	1.2	1.9	1.1	2.3

Ammonia-Nitrogen (NH_4-N), ppm

Depth, cm	September, 1973									December, 1973								
0-5	2.5	3.6	2.4	6.9	2.9	3.0	3.0	3.4	4.7	7.3	1.8	1.4	2.7	1.6	4.9	2.1	2.1	2.3
5-10	2.2	3.4	2.2	2.6	3.2	1.7	2.5	3.1	4.5	3.3	1.5	1.3	2.5	1.5	3.3	2.1	2.3	2.0
10-15	2.2	1.6	2.0	1.7	1.8	1.5	3.7	2.5	2.5	2.4	1.6	1.5	2.2	1.5	1.7	1.8	2.4	2.2
15-20	1.6	2.8	2.0	2.5	7.8	4.8	0.0	2.7	2.3	2.7	1.5	1.4	1.9	1.4	1.4	1.6	2.2	2.3
20-25	2.4	2.3	2.9	2.6	1.5	2.5	3.6	2.2	1.4	2.6	1.6	1.4	1.6	1.9	1.2	1.6	2.0	2.2
25-35	3.2	3.4	2.2	2.4	2.9	2.4	3.2	2.2	1.9	2.1	1.2	1.5	1.5	1.4	1.2	1.6	1.7	3.2
35-45	1.5	1.9	2.2	2.0	2.1	3.6	3.1	2.4	5.7	2.5	1.2	1.6	1.8	1.3	1.3	1.5	1.6	1.8
45-55	1.8	1.9	1.2	1.9	2.0	8.8	3.4	2.8	3.4	2.3	1.1	1.3	1.4	1.2	1.1	.9	1.5	1.6
55-65	3.6	2.3	2.8	2.0	2.7	4.4	4.1	2.2	3.4	1.9	1.2	1.9	1.2	1.8	1.8	1.5	1.9	1.8
65-75	2.2	2.0	4.7	0.0	2.2	1.9	3.6	3.0	3.1	1.8	1.1	2.2	1.0	1.7	1.4	1.5	1.3	1.3

Magnesium (Mg), ppm

Depth, cm	September, 1973 Plot									December, 1973 Plot								
	1-H	2-L	3-M	4-H	5-M	6-L	7-H	8-L	9-M	1-H	2-L	3-M	4-H	5-M	6-L	7-H	8-L	9-M
0-5	73	57	68	77	51	54	56	54	54	32	29	30	31	32	37	30	29	32
5-10	60	64	57	34	21	21	38	32	36	26	27	25	28	23	35	26	25	24
10-15	23	20	30	22	18	12	21	12	22	21	21	19	19	17	23	16	11	13
15-20	14	14	14	18	11	6	11	7	11	13	9	18	16	12	12	12	9	15
20-25	9	7	7	17	7	4	12	9	10	9	8	20	11	9	8	10	14	9
25-35	7	3	3	7	3	3	10	9	10	6	4	12	7	8	7	10	11	11
35-45	10	3	5	8	5	4	15	8	12	8	5	8	10	7	5	13	14	14
45-55	8	2	2	6	2	2	20	5	19	6	2	5	7	5	3	15	15	13
55-65	6	2	3	6	2	1	17	6	19	5	4	6	8	4	5	14	15	15
65-75	9	3	7	7	3	3	17	9	18	6	5	6	11	5	5	14	5	15

Phosphorus (P), ppm

Depth, cm	September, 1973									December, 1973								
0-5	117	49	72	100	65	39	47	12	26	158	50	58	94	82	55	48	12	85
5-10	52	18	30	30	16	12	15	5	8	102	32	41	41	31	17	16	7	48
10-15	20	13	20	14	20	11	15	6	5	62	22	26	27	27	15	6	2	8
15-20	15	19	18	20	17	12	5	4	3	42	18	22	24	15	8	5	2	4
20-25	16	15	11	11	18	11	4	8	3	26	30	14	22	7	12	3	3	7
25-35	7	8	8	5	8	6	3	8	5	14	25	11	10	13	3	3	1	1
35-45	9	6	16	5	7	5	5	3	7	13	10	11	13	7	6	2	2	3
45-55	5	5	3	4	3	4	5	7	4	11	5	6	7	4	3	2	1	4
55-65	6	5	5	6	3	2	4	5	3	9	11	6	9	2	7	4	2	1
65-75	3	5	5	2	3	2	5	4	3	7	4	3	9	3	4	4	4	2

Potassium (K), ppm

Depth, cm	September, 1973									December, 1973								
0-5	101	103	129	113	107	103	121	105	107	132	116	90	155	130	77	97	68	76
5-10	99	46	85	96	64	31	81	16	55	132	74	88	135	113	56	78	48	61
10-15	78	25	35	60	36	11	49	8	21	101	28	63	89	51	36	43	15	29
15-20	67	17	20	46	18	8	32	10	11	85	20	43	87	61	23	31	11	48
20-25	26	9	14	36	9	5	28	8	13	56	21	74	48	30	24	23	21	22
25-35	23	10	9	20	6	6	36	8	10	40	11	29	48	25	9	19	18	24
35-45	22	8	9	17	8	7	28	18	16	39	14	47	[illegible]	18	17	23	14	29
45-55	23	7	10	19	10	7	12	9	14	34	9	39	[illegible]	20	10	13	13	14
55-65	19	8	27	14	7	7	16	9	12	29	14	48	73	60	32	20	19	18
65-75	17	18	23	15	18	19	13	11	11	34	30	53	102	45	26	31	28	18

APPENDIX C1. (continued)

pH

Depth, cm	September, 1973									December, 1973								
	1-H	2-L	3-M	4-H	5-M	6-L	7-H	8-L	9-M	1-H	2-L	3-M	4-H	5-M	6-L	7-H	8-L	9-M
0-5	5.7	5.9	6.2	6.3	6.5	6.3	5.6	5.8	5.9	5.9	6.4	6.1	6.4	6.4	6.7	5.9	5.8	6.1
5-10	5.8	5.4	6.0	6.3	6.1	5.5	5.5	5.1	5.4	.8	6.3	6.1	6.4	6.3	6.5	.8	.7	5.6
10-15	5.3	5.2	5.6	5.6	5.6	4.9	4.8	4.6	5.2	.5	5.9	5.8	6.0	6.0	6.2	.4	.3	.2
15-20	4.7	4.8	5.0	5.3	4.9	4.7	4.4	4.5	4.8	.2	.5	.8	5.5	5.7	5.5	.2	.1	0
20-25	4.2	4.6	4.9	5.1	4.8	4.6	4.4	4.5	4.6	1	.3	.7	.3	.8	.4	.1	.2	1
25-35	4.2	4.5	4.8	4.8	4.8	4.7	4.2	4.5	4.6	2	.3	.4	.2	.6	.2	.2	.2	2
35-45	4.4	4.3	4.6	4.4	4.6	4.7	4.4	4.4	4.5	2	.3	.5	.3	.5	.3	.1	.1	2
45-55	4.0	4.1	4.2	4.1	4.3	4.4	4.4	4.4	4.7	0	.0	.1	.0	.2	.1	.4	.3	3
55-65	4.1	4.1	4.1	4.0	4.2	4.2	4.4	4.3	4.7	4.7	.2	.0	4.9	4.9	4.6	.3	.3	1
65-75	3.8	4.1	4.2	4.1	4.1	4.2	4.4	4.4	4.6	4.5	4.7	5.0	4.8	4.9	4.7	5.1	4.7	5.1